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A STUDY OF EXPLOSIONS OF GASEOUS MIXTURES

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BY

A. P. KRATZ

AND

C. Z. ROSECRANS

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BULLETIN No. 133

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UNIVERSITY OF ILLINOIS
ENGINEERING EXPERIMENT STATION

BULLETIN NO. 133 AUGUST, 1922

A STUDY OF EXPLOSIONS OF GASEOUS MIXTURES

BY

A. P. KRATZ

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A STUDY OF EXPLOSIONS OF GASEOUS MIXTURES

I. General Statement Concerning Investigation

1. *Preliminary Statement.*—An investigation of explosions of gaseous mixtures at constant volume was undertaken by the Engineering Experiment Station in 1914, when C. R. Richards, Dean of the College of Engineering and Director of the Engineering Experiment Station—at that time Head of the Department of Mechanical Engineering—outlined an extensive series of experiments and defined the scope of the investigation which was to follow. Apparatus was designed and a few results were obtained showing the effect of the shape of the explosion vessel, and of turbulence at the time of firing, but it was found necessary to discontinue the work. In 1919 part of the apparatus was re-designed and work was resumed. This bulletin is a preliminary report of the methods pursued and the results thus far obtained.

2. *Scope of Investigation.*—The investigation as originally planned was to consist of experiments on the simple gases—namely, hydrogen, carbon-monoxide, methane, and possibly acetylene—to determine the effect of varying proportions of gas and air, initial pressure, shape of the explosion vessel, ratio of its volume to its area, position of ignition, and turbulence during the time of ignition, upon the rate of inflammation, maximum pressure, and time of explosion. The work was next to be extended to various combinations of gaseous fuels, including the commercial fuels used in practice for internal combustion engines, in order to determine the effect of different proportions of the various constituents upon the rate of inflammation, maximum pressure, and time of explosion.

Tests were also to be made with the temperature of ignition corresponding to the temperature found at the end of compression in different types of commercial internal combustion engines. It was expected that some method of heating could be developed that would preclude flameless combustion taking place at the surface of the heating element before the ignition temperature was attained. From

this series conclusions might be drawn relative to the effect of variations in the carbon-hydrogen ratio upon factors leading to pre-ignition in internal combustion engines.

3. *Object of Investigation.*—The immediate object of the series of tests reported in this bulletin was a study of the physical phenomena involved in the explosions of various mixtures of illuminating gas and air. This includes the determination of the effect of different shaped explosion vessels, and of turbulence at the time of ignition, as well as a study of the heat loss from the burning mass of gas.

Any problems connected with the chemical changes involved have not been considered within the scope of the investigation.

4. *Acknowledgment.*—Acknowledgment is due to C. R. RICHARDS, Dean of the College of Engineering, for his constant interest and encouragement, his many helpful suggestions, and for the original outline defining the scope of the investigation.

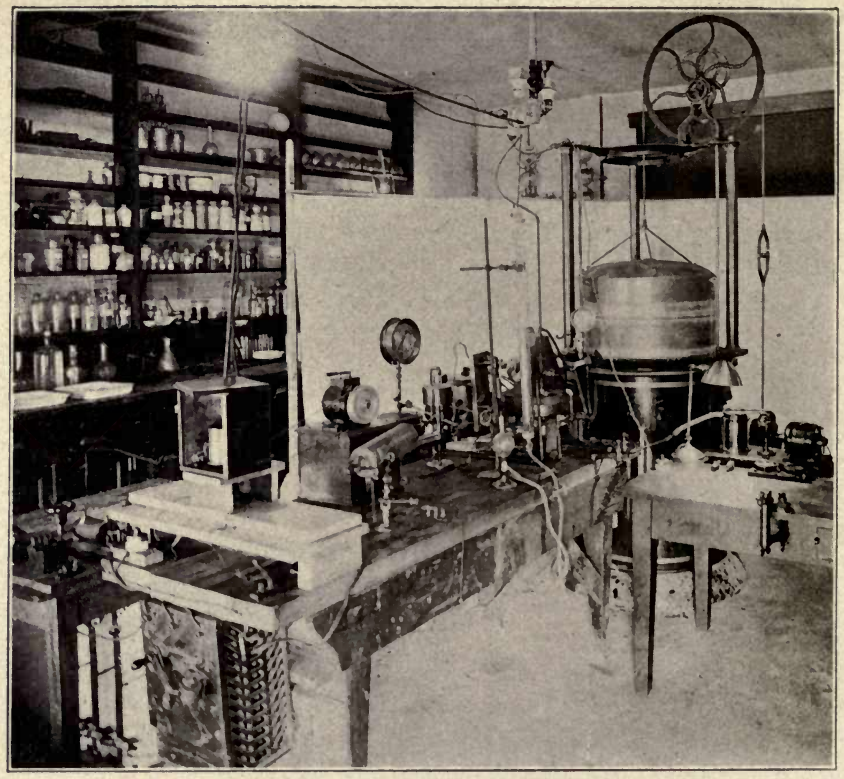


FIG. 1. GENERAL VIEW OF EXPLOSION APPARATUS

II. Description of Apparatus

5. *Explosion Apparatus.*—A general view of the apparatus used in this investigation is shown in Fig. 1. At the time the photograph was taken a conical explosion vessel was in use. The apparatus consisted of an explosion vessel, an indicator with a lamp and recording drum, a tuning fork, a gas holder, a small motor-driven vacuum pump, a measuring burette, a dead-weight tester for calibrating the indicator, and an induction coil. The photograph also shows the motors used for driving the fan in the explosion vessel and the recording drum for the indicator. This apparatus was essentially the same for all of the tests. At times it was found desirable to modify some of the details of the recording mechanism in order to facilitate the manipulation and to overcome vibration, but no changes in principle were made.

6. *Explosion Vessels.*—The explosion vessel in all cases consisted of a head of the desired shape bolted to a heavy base-plate, all parts being made of steel castings. Four different shaped heads were used, cylindrical, conical, hemispherical, and L-shaped, the last-named being similar to the combustion space of an L-head gasoline engine cylinder. The dimensions of these heads are shown in Fig. 2. They enclosed the same volume in all cases, and were designed to withstand explosion pressures of 2500 lb. per sq. in. They were centered accurately on the base-plate and were fastened to it by eight 1¼-in. cap screws. A thin paper gasket was used to prevent leakage. A 4-in. fan, having two blades and driven by a shaft passing through the center of the base-plate, afforded a means of agitating the mixture in the vessel. Threaded connections were provided in the walls of the vessels for the ignition plug and for gas piping. A diagram of the piping connections is shown in Fig. 3. Each vessel had two connections diametrically opposite for admitting and exhausting the air and gas. Heavy needle valves made from steel bars were used at these two points. All other valves were standard brass needle valves.

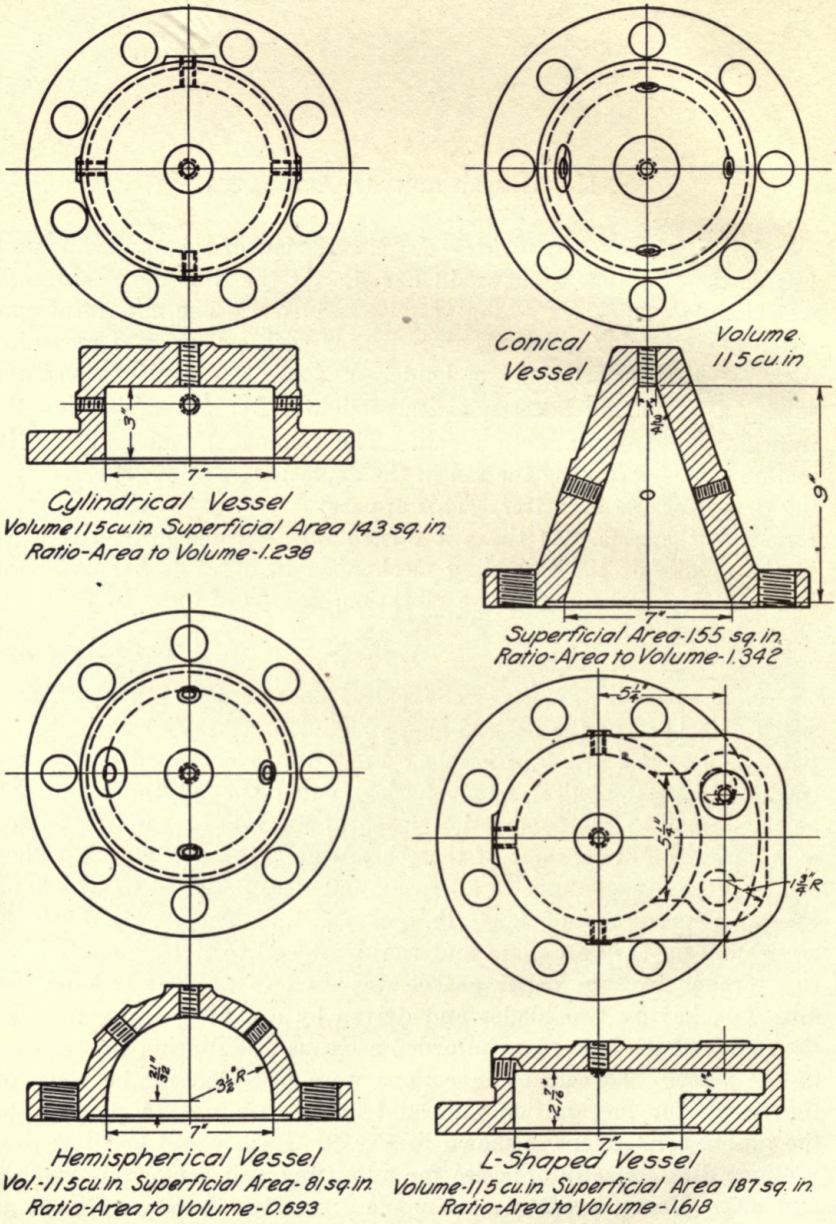

Cylindrical Vessel
Volume 115 cu. in. Superficial Area 143 sq. in.
Ratio-Area to Volume-1.238
Conical Vessel
Volume 115 cu. in
Superficial Area-155 sq. in.
Ratio-Area to Volume-1.342
Hemispherical Vessel
Vol.-115 cu. in. Superficial Area-81 sq. in.
Ratio-Area to Volume-0.693
L-Shaped Vessel
Volume-115 cu. in. Superficial Area 187 sq. in.
Ratio-Area to Volume-1.618

FIG. 2. FORMS OF EXPLOSION VESSELS

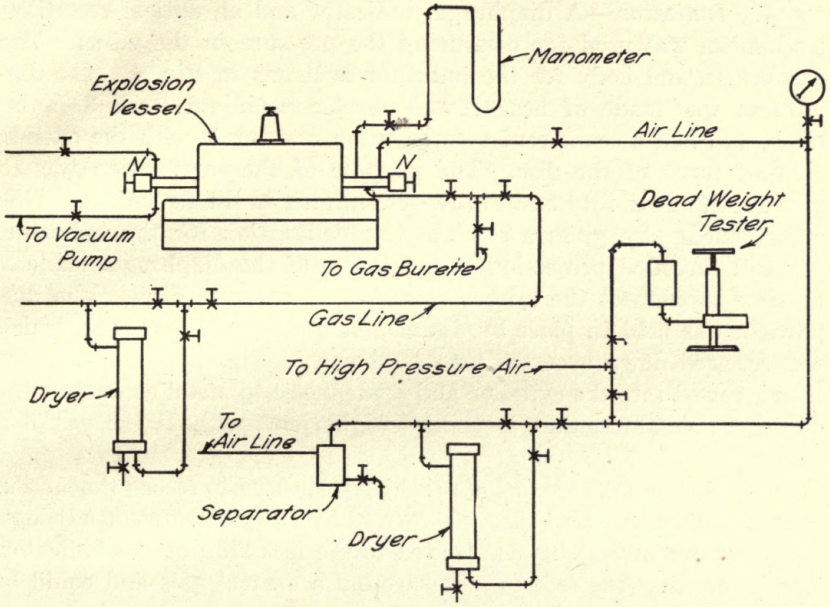


FIG. 3. GAS AND AIR PIPING

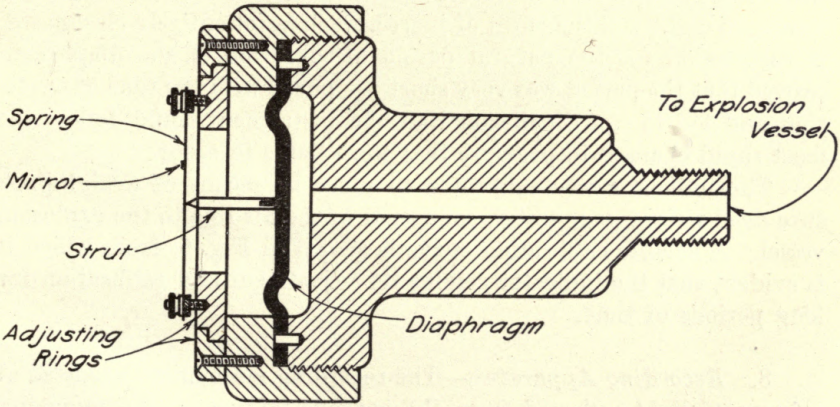


FIG. 4. INDICATOR DIAPHRAGM AND BODY

7. *Indicator.*—A diaphragm indicator and an optical recording mechanism was used for measuring the pressure in the vessel. The diaphragm and body for the indicator is shown in Fig. 4. The diaphragm was made of heat-treated chrome-vanadium steel, 3/64 in. thick, and had a semicircular corrugation concentric with the outside circumference of the disc. The purpose of the corrugation was to give greater flexibility and to prevent slipping in the fastenings. This arrangement also gives a straight line calibration for the indicator. A small threaded projection at the center of the diaphragm made it possible to connect the mirror system used for recording. The diaphragm was held in place by dowel pins and by the lock-ring, which was screwed down over the base as shown in Fig. 4. The body was then screwed into the cylinder and made metal to metal contact at the 45 degree shoulder, thus insuring a tight joint without the use of a gasket.

Fig. 5 shows the mounting for the mirror used to record the motion of the diaphragm. The base was formed by two concentric steel rings, the outer one of which was screwed to the lock-ring of the indicator. The inner ring was free to move around a central axis and could be locked in place by means of the four cap screws. The mirror was mounted on a steel spring extending between two studs. A small strut, screwed to the projection on the diaphragm, pressed against the spring at the center and communicated the motion of the diaphragm to the spring, which in turn tilted the mirror. This arrangement afforded a wide range of adjustment for the indicator mirror. The moving parts were very light and the effect of inertia was almost entirely eliminated. A calculation for the natural period of vibration of the diaphragm proved that the period was very short compared with the time of explosion and led to the conclusion that the instrument could follow the most rapid changes in pressure that were liable to occur.

The indicator was calibrated in place by means of a high-pressure dead-weight gage-tester, connected in the air line to the explosion vessel. A sample calibration curve is shown in Fig. 6, from which it is evident that the indicator retains its adjustment and calibration for long periods of time.

8. *Recording Apparatus.*—The recording mechanism consisted of a beam of light reflected from the concave mirror on the indicator, and focused on a strip of photographic paper carried on a revolving

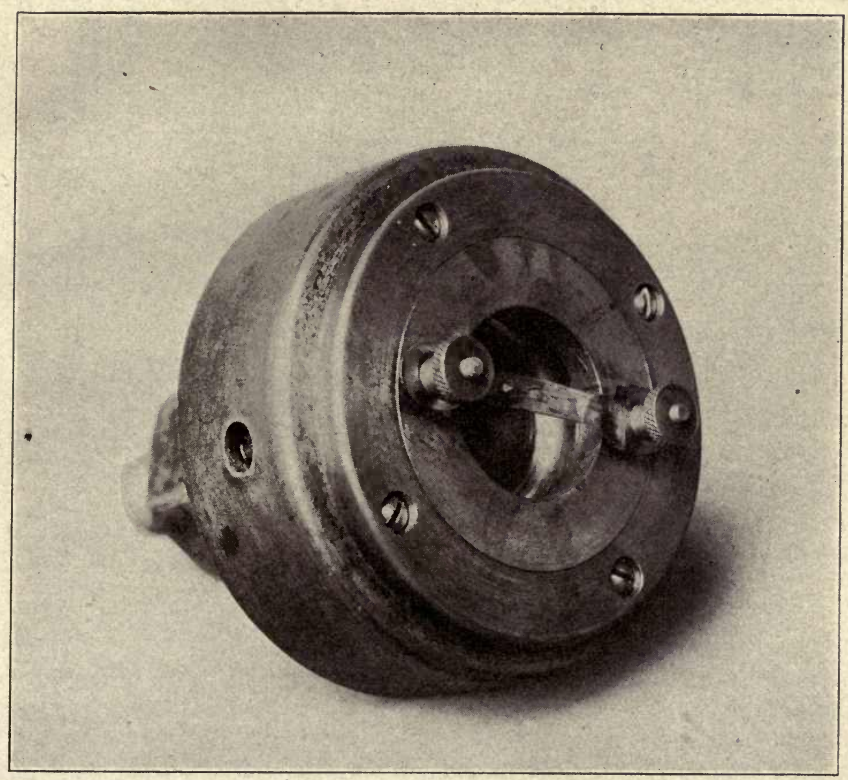


FIG. 5. INDICATOR WITH MIRROR ATTACHED

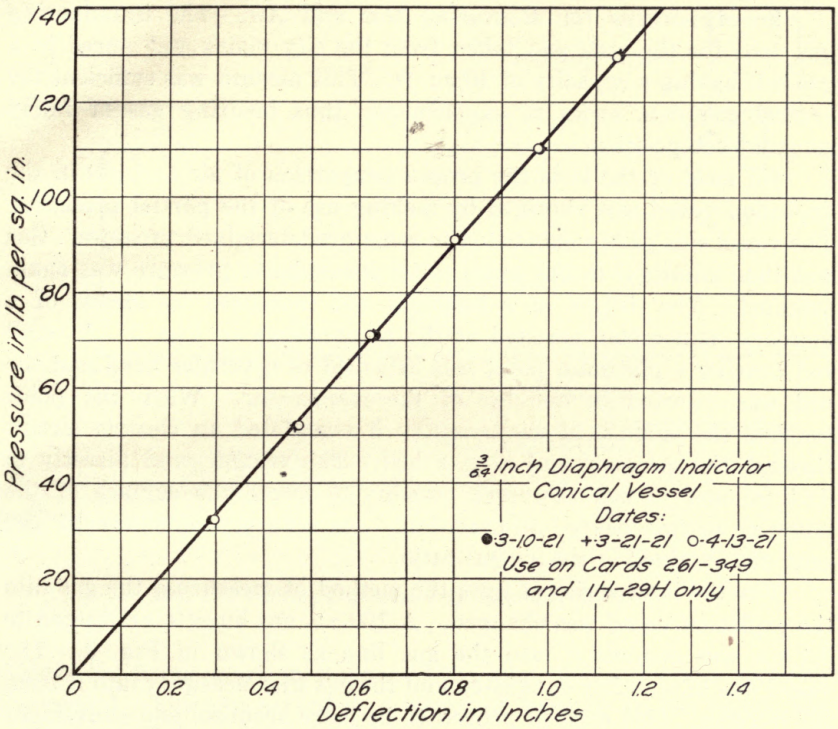


FIG. 6. CALIBRATION CURVE FOR OPTICAL INDICATOR

drum. The drum was 11 in. in circumference and was driven through a worm gear by a variable speed motor. A small enclosed arc lamp was used to project the beam of light on the mirror. A piece about 1/16 in. in diameter, cut from a concave mirror of 1 meter radius of curvature, was used and the arc light and drum were placed at such distances that a well defined image of the crater of the arc was obtained on the photographic paper. The records when developed showed a very narrow black line for the motion of the mirror. A special recording paper known as "Eastman Recording Paper No. 1" was used. This paper proved to be sufficiently rapid to give clear records, and was much more convenient to use than films. All records were developed immediately after being taken.

9. *Apparatus for Measuring Gas and Air.*—The illuminating gas used for the tests was taken from the city mains and stored in a gas bell having a capacity of 10 cu. ft. This amount was sufficient for several complete series of experiments, thus insuring gas of fairly constant composition.

On most of the tests the proper proportion of air and gas in the explosion vessel was obtained by making use of the partial pressures. The vessel was partly exhausted to some predetermined pressure. Gas was then admitted to the vessel until atmospheric pressure was again attained. The degree of exhaustion was measured by means of a mercury manometer inserted at the point shown in Fig. 3. A small rod bearing a platinum point was attached to a vernier head and the rod was inserted in one leg of the manometer. When the point touched the surface of the mercury it completed an electric circuit through the mercury and rang a bell. The vernier read directly to 0.01 in. and it was therefore possible to locate the surface of the mercury to this degree of precision. An accuracy of about 0.1 per cent was obtained in the air-gas ratio.

For the later series of tests the method of measuring the gas into the explosion vessel was changed. A 100-c.c. gas burette graduated to 0.1 c.c was connected into the gas line as shown in Fig. 3. The vessel was then partly exhausted and the gas was measured into it from the burette. This method proved to be more accurate and convenient than the first method described.

10. *Ignition Apparatus.*—The mixture in the explosion vessel was ignited by means of a spark passed across a 0.03 in. gap on a standard mica-insulated automobile spark-plug. A ¾-in. induction coil was used, drawing current from a 6-volt storage battery. The wiring diagram is shown in Fig 7. A contact attached to the circumference of the recording drum completed the primary circuit of the induction coil, and induced the spark at the gap in the spark-plug, thus igniting the mixture in the explosion vessel. A switch was provided in the primary circuit. The drum could then be started some time before the explosion was desired, and when it was revolving at constant speed, the switch could be closed and the explosion occurred when the contact was made on the recording drum. A small spark-gap in series with the plug was placed close to the sensitized paper on the revolving drum. A spark passed across this gap at the same

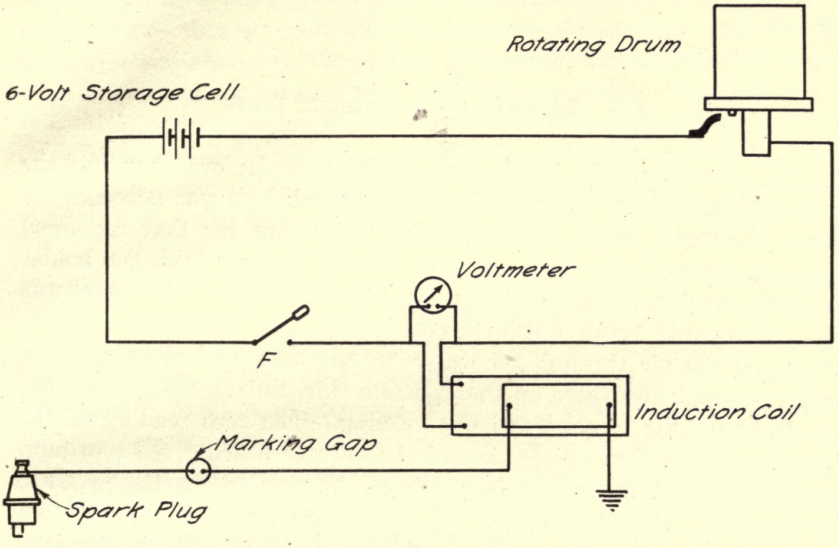


FIG. 7. WIRING DIAGRAM FOR IGNITION SYSTEM

instant the firing spark took place at the plug, and a dot was made on the record. This dot served as a means of locating on the record the exact time of firing. It should be noted that the time of firing did not coincide with the time at which the pressure in the vessel began to increase. The latter took place subsequent to the passing of the spark. When contact was made at the circumference of the drum, the circuit remained closed for about 0.1 sec., and from 6 to 10 separate discharges occurred across the spark-gap.

11. *Timing Apparatus.*—A tuning fork having a frequency of 100 vibrations per second was used in order to obtain the time of explosion. The tuning fork was electrically driven and had a small concave mirror mounted on one leg close to the base. A beam of light from the arc lamp was reflected from the mirror and focused on the recording paper placed on the revolving drum. When the fork was in vibration a sine curve was traced on the record, and the time could be computed by counting the peaks on the curve.

III. Method of Conducting Tests

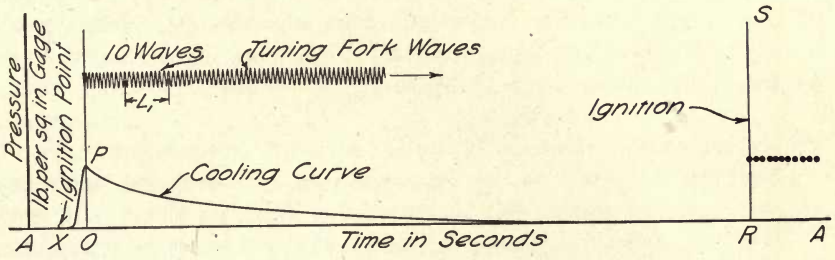
12. *Procedure in Making an Explosion.*—Before charging the explosion vessel with the mixture to be exploded, it was necessary to purge the vessel itself and the piping from any gas that remained from a previous test. Gas was first allowed to flow from the holder into the vessel in order to fill the line with fresh gas. The vessel was then thoroughly swept out with compressed air. This was done by admitting the air through the valve on one side, and allowing it to escape through the valve on the opposite side, during which time the fan inside of the vessel was kept running. The zero reading of the manometer was then observed, and the vernier bearing the platinum contact point was set in a position to give the required partial pressure for the gas. All valves except the one in the line from the vacuum pump were then closed, and the vessel was exhausted until the mercury in the open leg of the manometer fell below the contact point. Air was then allowed to enter the vessel very slowly until the bell in the manometer circuit gave warning that the surface of the mercury had just touched the contact point. When this was the case, the vacuum within the vessel was equal to the required partial pressure for the gas. The air valve was then closed, the gas valve was opened, and gas was allowed to enter until the pressure in the vessel was equal to that of the atmosphere. The valves, *N*, Fig. 3, were then closed.

In the later tests, where the measuring burette was used, the procedure outlined was somewhat modified. After purging the vessel it was exhausted to a pressure of about 10 in. of mercury absolute. The air valve was closed, and the required volume of gas was measured in from the burette. The exhaust valve was then opened, and air was allowed to enter the vessel until the pressure rose to that of the atmosphere. The valves, *N*, were then closed. The fan was run at about 300 rev. per min. during admission of the gas and was left running for a time considered sufficient to insure thorough mixing of the gas and air. If turbulence was desired the fan was allowed to run while the explosion was made.

The room was darkened, the sensitized paper was placed on the drum and the driving motor for the drum was started. The mirror on

the tuning fork was covered and the arc light put in operation. The shutter was then opened and the zero or atmospheric line for the indicator was traced on the record, after which the shutter was closed. The mirror on the tuning fork was next uncovered, the fork set in vibration, the shutter on the drum opened again, and the firing switch *F*, Fig. 7, closed. When the contact at the circumference of the drum came into position the charge was automatically fired. The paper was then removed from the drum and placed in the developer.

13. *Calculation of Maximum Pressure and Time of Explosion.*— Typical records are shown in Figs. 8 and 26. The line *A-A*, Fig. 8, is the zero or atmospheric pressure line which was traced before the explosion was made; the serrated line represents the record of the tuning fork; and the line with the single peak is the record of the explosion and the subsequent cooling of the mixture. The first dot of the dotted line indicates the time at which the spark took place. *OP* is a line drawn perpendicular to the zero line and passing through the highest point on the pressure curve. In order to obtain the ignition point *X*, on the pressure curve *RS*, a perpendicular from the base line, is erected through the first dot on the spark curve. The distance between the position of the auxiliary spark gap, placed close to the paper, and the line representing the vertical travel of the spot of light from the indicator is then measured back from the foot of the perpendicular at *R*. This distance was determined by taking a sep-



Card No. 322
Initial Pressure-Atmospheric Air Gas Ratio-6
Maximum Pressure-82.5 lb. per sq. in. Initial Temperature-75°F.
Time of Explosion-0.054 Second

FIG. 8. TYPICAL RECORD OF EXPLOSION

arate record obtained while passing the spark with no explosive mixture in the vessel and with the drum at rest. For any given adjustment of the indicator the distance was constant. The horizontal distance, XO, is a measure of the time of explosion.

The distance XO is translated into seconds as follows. Let

N_1 = any arbitrary number of vibrations of the tuning fork, usually chosen as 10;

N_2 = the number of vibrations of the fork per second;

N = the number of vibrations contained in the distance $L = XO$;

L = the distance XO measured from the record;

L_1 = the horizontal distance covered by N_1 vibrations of the fork (Fig. 8);

T = time of explosion in seconds;

$$T = \frac{N}{N_2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

$$\frac{L}{L_1} = \frac{N}{N_1}, \text{ or } N = \frac{LN_1}{L_1} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

$$T = \frac{LN_1}{L_1 N_2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

Since $L = XO$, N_1 was usually chosen as 10, and the fork when calibrated was found to average 98 vibrations per second, equation (3) becomes:

$$T = \frac{0.102\ (XO)}{L_1}$$

IV. Results

14. *Phenomena Concerned in Gaseous Explosions.*—If a homogeneous mixture of any inflammable gas and air at atmospheric temperature and pressure is enclosed in a vessel, the walls of which are also at atmospheric temperature, and the mixture ignited, inflammation will take place at a rate depending on the nature of the mixture. The heat developed by the combustion will increase the temperature of the gases, thus developing pressure within the vessel, but at the same time a loss of heat will take place from the gases to the walls of the vessel, thus tending to lower the temperature of the mixture and the resultant pressure. At some time during the process of combustion the loss of heat to the walls will balance the additional heat being evolved by the combustion, and the pressure will cease to rise. If a continuous record is made of the pressure in the vessel the curve will attain a maximum at this point, designated hereafter as the "maximum pressure." The maximum pressure finally attained will not be affected by the time taken to complete the combustion other than by the amount of cooling during this period, but will be a function of the completeness of the combustion at the time that thermal equilibrium has been established. After maximum pressure has been reached the gas continues to cool by losing heat to the walls of the vessel, and the pressure decreases. If the cooling is allowed to continue indefinitely the gas and the vessel will ultimately cool to atmospheric temperature and if no contraction due to chemical combination has taken place, the pressure in the vessel will again be atmospheric.

The time elapsing from the instant of ignition to that of attaining maximum pressure will be designated as the "time of explosion." This time is not as much a function of the energy liberated by the chemical reaction as it is of mechanical conditions within the mixture tending to bring the different parts of the mixture into more intimate contact, thus facilitating the communication of the flame from any one part to those adjacent.

Both maximum temperature and time of explosion will be influenced by the "air-gas ratio," or the ratio by volume of air to gas

in the original charge and the shape of the vessel within which the explosion takes place.

15. *General Statement Concerning Gas Used.*—The gas used in most of the tests was illuminating gas taken from the city mains. It was stored in a water sealed gas holder, and therefore was saturated with water vapor.

The earlier experiments on the cylindrical and those on the L-shaped vessel were made in 1915, while the later ones on the cylindrical, hemispherical, and conical vessel, were made in 1921. The calorific value and the hydrogen content of the gas was less in 1921 than it was in 1915. It was found by comparing the results obtained on the cylindrical head at the two different times that a correction could be made for the difference in calorific value of the gas. All the results of the earlier series were therefore corrected to bring them into conformity with the later series.

A comparison between the gas used in 1915 and that used in 1921 is given in Table 1.

16. *Designation for Tests.*—The tests have been grouped into a number of series in order to render them more convenient for the

TABLE 1

ANALYSES OF ILLUMINATING GAS

Constituent	Year 1915	Year 1921
CO_2 per cent	3.7	7.2
O_2 per cent	0.6	0.7
CO per cent	20.9	13.7
CH_4 per cent	28.8	23.6
C_2H_4 per cent	5.5	7.8
C_6H_6 per cent	2.8	2.7
H_2 per cent	18.7	11.7
N_2 per cent	19.0	32.6
*Calorific value in B. t. u.	562	504

*The calorific value is the lower calorific value based on one cu. ft. of gas at 62 deg. F. and 29.92 in. Hg.

purpose of discussion. Each series had for its object the determination of the effect of some one factor, as turbulence, conditions of ignition, or shape of explosion vessel, upon the maximum pressure and time of explosion, and consisted of a number of explosions made with different mixtures of gas and air ranging from the richest to the leanest mixture that could be exploded. No attempt was made to determine the exact limits of inflammability of the gas, but the mixtures were varied by half units in the scale of air-gas ratios until one was found that failed to explode. Some explosions of hydrogen and air were also made in the conical vessel in order to compare the experimental values of the maximum pressure with those obtained from theoretical considerations. Table 2 gives a schedule of the various series.

17. *Preliminary Tests.*—The curves obtained from Series 1 are shown in Fig. 9. This series was run on the cylindrical vessel,

TABLE 2
SCHEDULE OF TESTS

Series No.	Vessel No.	Shape of Vessel	Turbulence
1	1	Cylindrical	Without
2	2	L-shaped	Without
3	2	L-shaped	With
4	2	L-shaped	Without
5	2	L-shaped	With
6	2	L-shaped	Without
7	2	L-shaped	With
8	1	Cylindrical	Without
9	1	Cylindrical	With
10	3	Conical	Without
11	3	Conical	With
12	3	Conical	Without
13	3	Conical	With
14	4	Hemispherical	Without

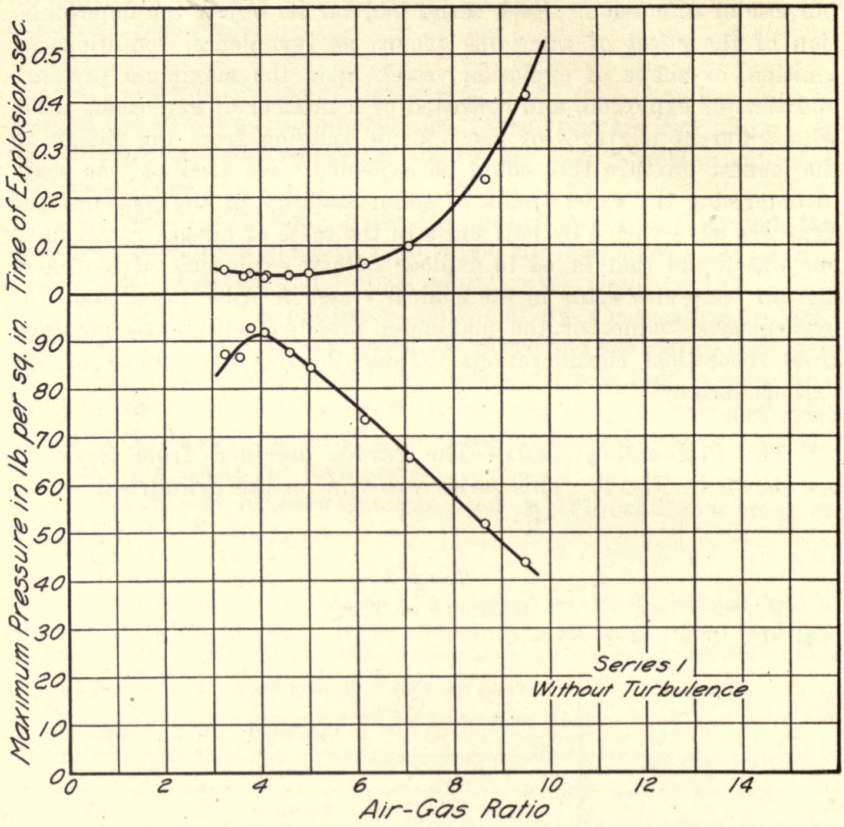


FIG. 9. EXPLOSION CURVES FOR CYLINDRICAL VESSEL

with ignition occurring flush with the upper surface at the center and without turbulence. The gas was admitted without having the fan running and the mixture was exploded after being allowed to stand for about 10 min. These curves are typical of all the explosion curves obtained. The series was run in 1915 with gas of a higher heating value than that used later, and the curves are given here because reference will be made to them in the study of the effect of the shape of the vessel upon the maximum pressure and time of explosion.

The maximum pressure occurred with an air-gas ratio of 3.9 to 1. The theoretical value of the air-gas ratio for maximum pressure is about 6 to 1. The discrepancy between these two figures may be explained by the fact that the 6 to 1 mixture contains a relatively larger amount of nitrogen than the stronger mixture, and the heat used to raise the temperature of the nitrogen reduces that which would otherwise be available for causing an increase of pressure.

The maximum pressure of 92.5 lb. per sq. in. and minimum time of explosion of 0.04 sec. are in close agreement with values of 91.0 lb. per sq. in. and 0.05 sec. which Dugald Clerk found for mixtures of Oldham gas and air.

18. *Turbulence during Ignition.*—The effect of turbulence at time of ignition for the L-shaped vessel is shown in the explosion curves of Figs. 10, 11, and 12. All the results for the L-shaped vessel were obtained with the same gas as that used for Series 1 and they are therefore strictly comparable. For Series 2 and 3, Fig. 10, the charge was fired flush with the upper surface and at the center of the main chamber. In Series 2 no stirring occurred at the time of firing, while in Series 3 the mixture was agitated by means of the fan during the time that the explosion took place. Series 4 and 5, Fig. 11, were run under the same conditions as Series 2 and 3 except that the charge was fired at the center of the valve chamber and flush with the upper surface of the vessel. In Series 6 and 7, Fig. 12, ignition occurred simultaneously in the main chamber and the valve chamber. Series 8 and 9, Fig. 13, were made using the cylindrical vessel, with ignition occurring flush with the upper surface and at the center of the head. These tests were made in 1921 and the gas used had a lower calorific value than that used for Series 1. For Series 10, 11, 12, and 13 the conical explosion vessel was used. In Series 10 and 11, Fig. 14, ignition took place at the vertex of the cone and in Series 12 and 13, Fig. 15, at a point 3 in. below the vertex.

In all cases the effect of turbulence at the time of ignition was very marked. The maximum pressure was increased and the time of explosion decreased for any given air-gas ratio. The effect was much more marked with the leaner mixtures than with the richer ones, indicating that with the lean mixtures combustion is retarded by the less intimate contact of the molecules. Turbulence also seemed to have a greater influence on the time of explosion, expressed as a

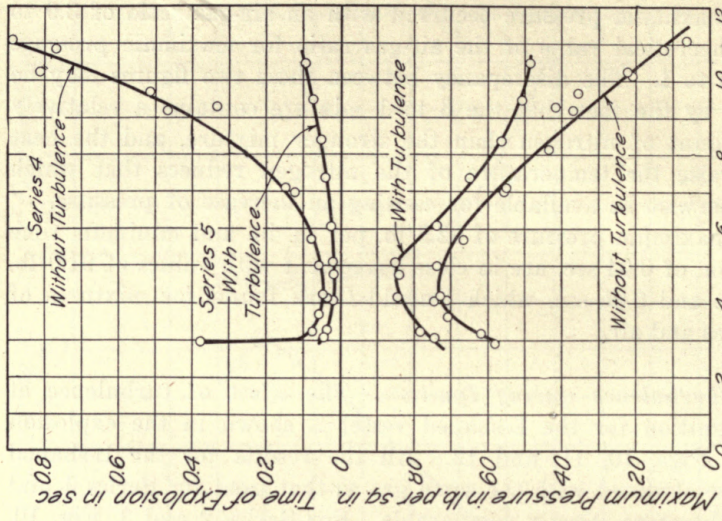


FIG. 11. EXPLOSION CURVES SHOWING EFFECT OF TURBULENCE FOR L-SHAPED VESSEL WITH IGNITION IN VALVE CHAMBER

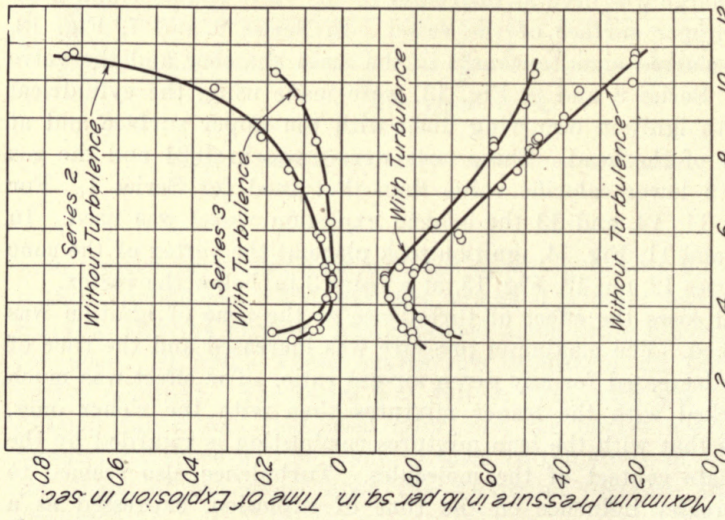


FIG. 10. EXPLOSION CURVES SHOWING EFFECT OF TURBULENCE FOR L-SHAPED VESSEL WITH IGNITION AT CENTER OF HEAD

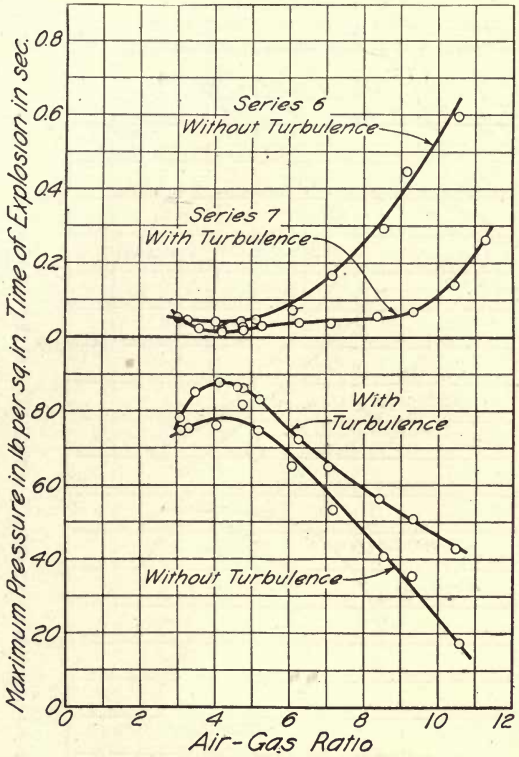


FIG. 12. EXPLOSION CURVES SHOWING EFFECT OF TURBULENCE FOR L-SHAPED VESSEL WITH IGNITION AT CENTER OF HEAD AND IN VALVE CHAMBER

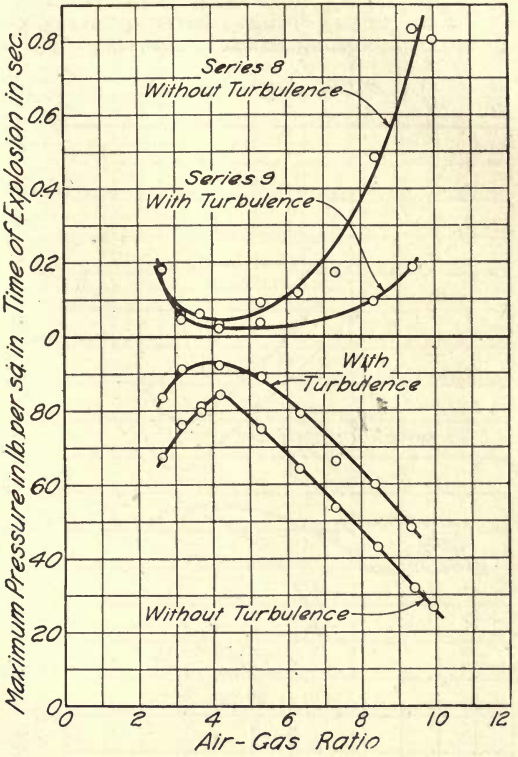


FIG. 13. EXPLOSION CURVES SHOWING EFFECT OF TURBULENCE FOR CYLINDRICAL VESSEL WITH IGNITION AT CENTER OF HEAD

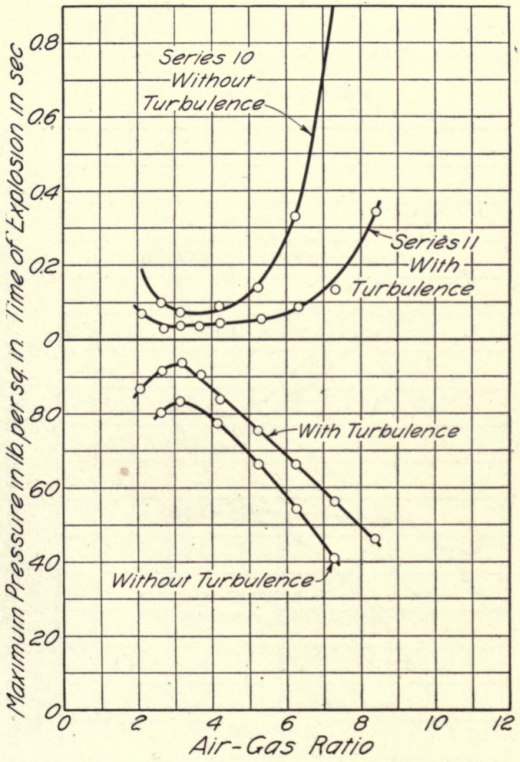


FIG. 14. EXPLOSION CURVES SHOWING EFFECT OF TURBULENCE FOR CONICAL VESSEL WITH IGNITION AT VERTEX

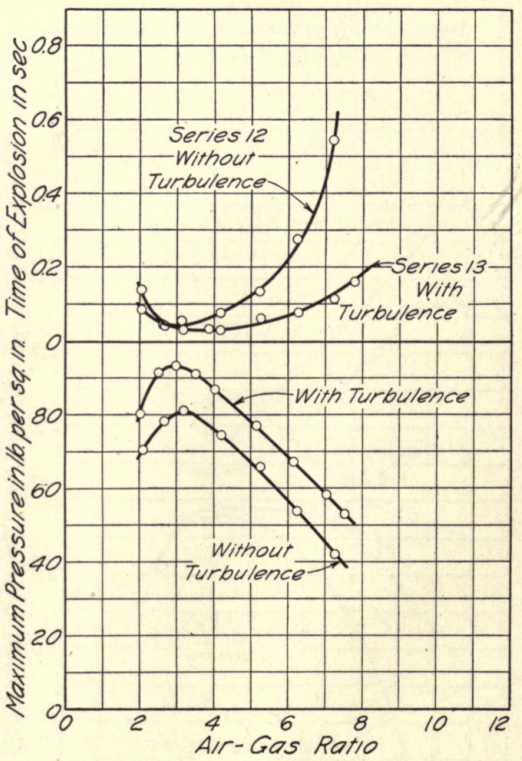


FIG. 15. EXPLOSION CURVES SHOWING EFFECT OF TURBULENCE FOR CONICAL VESSEL WITH IGNITION 3 IN. FROM VERTEX

percentage of the original time, than upon the maximum pressure. An explanation for this is given in Section IV, page 25. Besides increasing the maximum pressure for any given air-gas ratio, turbulence has the effect of increasing the value of the air-gas ratio at which the

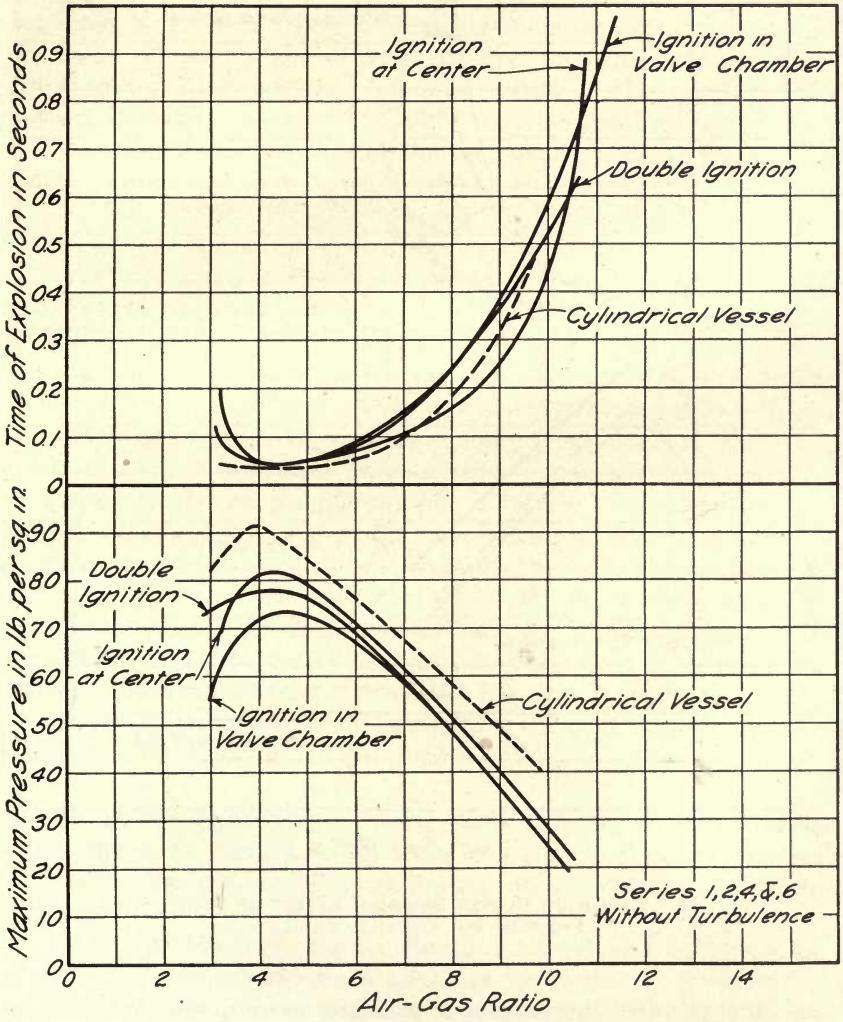


FIG. 16. EXPLOSION CURVES SHOWING EFFECT OF POSITION OF IGNITION FOR L-SHAPED VESSEL

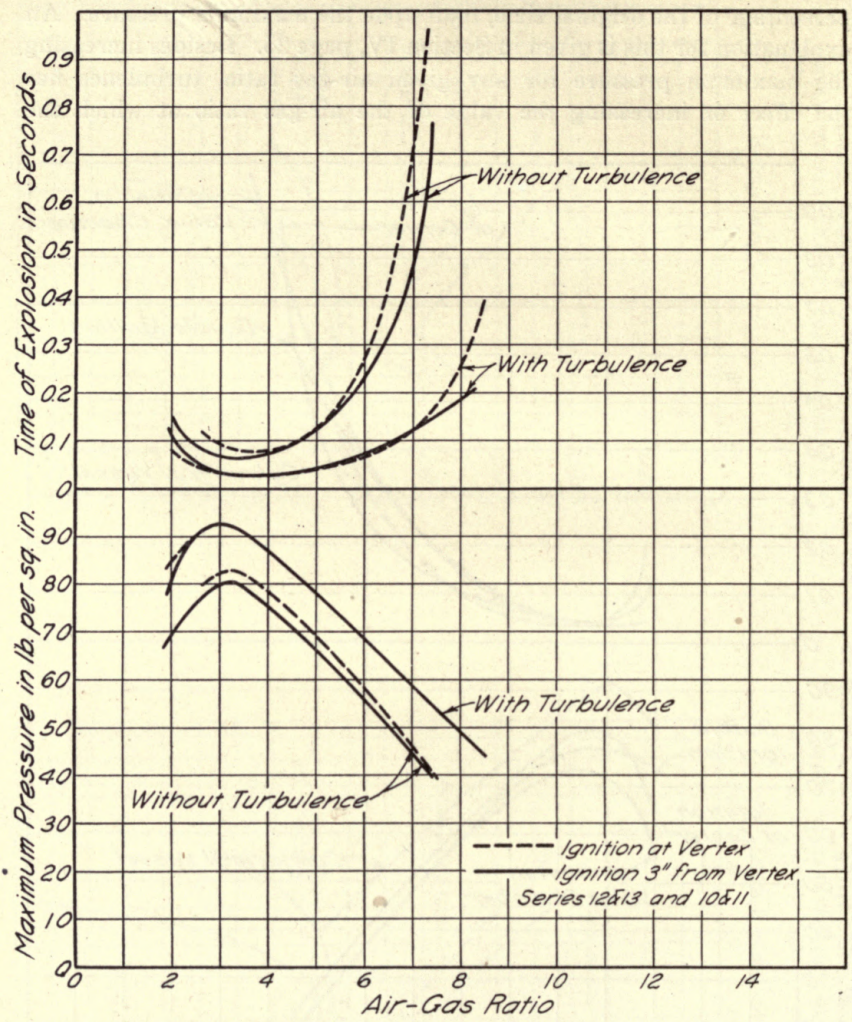


FIG. 17. EXPLOSION CURVES SHOWING EFFECT OF POSITION OF IGNITION FOR CONICAL VESSEL

maximum value of the maximum pressure occurs; that is, the best mixture corresponds to a leaner mixture when turbulence occurs than it does when no turbulence is present at the time of ignition.

19. *Position of Ignition Point.*—In Fig. 16 the curves resulting from Series 2, 4, and 6 have been superimposed in order to study the effect of the position of ignition. The curve for Series 1 has also been added and will be referred to in the discussion of the effect of the shape of the vessel. These curves show that the best position for ignition in an L-shaped combustion chamber is at the center of the head. When ignition occurs in a pocket the flame is cooled and is not propagated through the mixture as rapidly as when ignition takes place in the main chamber. Therefore, the slow burning mixture cools more during the explosion and the maximum pressure produced is not as great as it otherwise would have been.

In Fig. 17 the curves from Series 10, 11, 12, and 13 have been superimposed. These curves show that, when the fan in the vessel was not running, ignition at the vertex of the cone produced higher maximum pressures for all air-gas ratios than when ignition occurred 3 in. below the vertex of the cone. With turbulence, however, there seemed to be no difference in the maximum pressures produced with either position of ignition. This inconsistency may possibly be explained by the supposition that when ignition occurred at the vertex a pressure wave was started which advanced smoothly down the cone, expanding as though passing through a nozzle. When the gas was ignited further down within the cone, inflammation took place in all directions from the point of ignition, thus interfering with the formation of such a wave. Therefore, in the cases where no initial turbulence existed, the maximum pressure was higher when the mixture was fired at the vertex than it was when fired 3 in. below the vertex. When initial turbulence existed, however, the wave was broken up and the character of the combustion was the same for both methods of firing, as indicated by the coincidence of the two curves.

20. *Shape of Explosion Vessel.*—The explosion curves for Series 14 are shown in Fig. 18. This series was run on the hemispherical vessel with ignition occurring at the top of the vessel, and without turbulence.

In Fig. 16 the curve for the results from Series 1 for the cylindrical vessel was superimposed on those for Series 2, 4, and 6 for the L-shaped vessel. These series of tests were all made with the same gas in 1915 and are therefore strictly comparable. From this it may be noted that the maximum pressures for all air-gas ratios for the

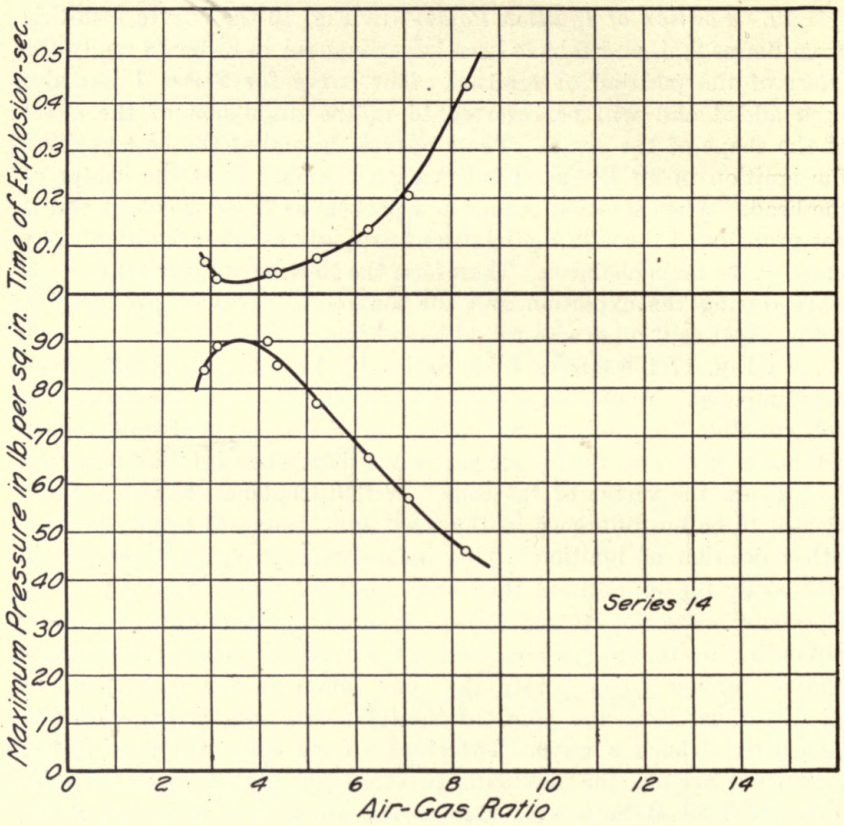


FIG. 18. EXPLOSION CURVES FOR HEMISPHERICAL VESSEL WITH IGNITION AT TOP AND WITHOUT TURBULENCE

cylindrical head were uniformly greater than those for the L-shaped head, even for the best condition of firing.

In Fig. 19 the curves for the results of Series 2, 8, 10, and 14 have been superimposed, in order to study the effect of the shape of the vessel upon the maximum pressure. Since Series 2 for the L-shaped vessel was run with a gas of different calorific value than that used for Series 8, 10, and 14, it was necessary to correct the curve for Series 2 in order to make all the curves comparable. This was done by comparing the curves of Series 1 and Series 8, which were

run in the same vessel with the two different gases, one in 1915 and the other in 1921. These curves were found to have exactly the same shape, while the curve for Series 1 was practically 10 per cent higher than that for Series 8. This difference in the curves was attributed partly to the fact that the calorific value of the gas was higher for Series 1 than for Series 8. The hydrogen content of the gas was also greater in the former case. The rate of inflammation would be greater and consequently the time of explosion would be less; hence the amount of cooling before the attainment of maximum pressure would be less. The maximum pressures obtained for the same vessel from the gas used in 1915 would therefore be higher than those obtained from the gas used in 1921. The curve for Series 2 for the L-shaped vessel run in 1915 has therefore been lowered by 10 per cent, and has been plotted as the equivalent curve for the L-shaped vessel in Fig. 19.

From Fig. 19 it is evident that the hemispherical shape is best for the explosion vessel. The conical and cylindrical vessels seem to be equally good, and both have a marked advantage over the L-shaped vessel. Since the same volume was enclosed by all of the vessels used, it is probable that the differences in maximum pressure observed are

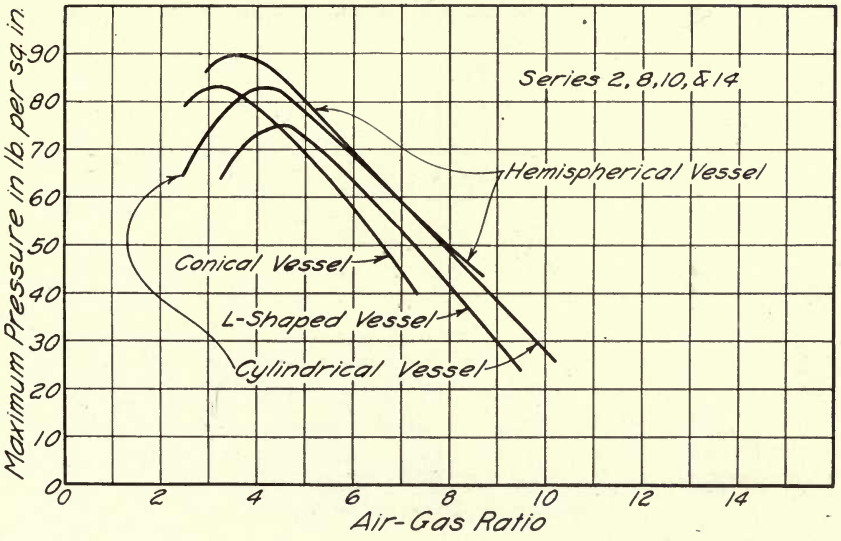


FIG. 19. MAXIMUM PRESSURE CURVES SHOWING EFFECT OF SHAPE OF EXPLOSION VESSEL

due to variation in the amount of surface exposed to the hot gases, which in turn influences the heat loss during the explosion. It is also possible that in the case of the L-shaped vessel complete combustion does not occur when the mixture is fired in the main chamber, since the flame must be cooled by passing into the narrow opening of the valve chamber.

Table 3 gives the ratio of the area of the inside surface to the volume for each vessel, and the greatest maximum pressures, taken from Fig. 19.

TABLE 3

RELATION BETWEEN MAXIMUM PRESSURE AND RATIO OF AREA TO VOLUME OF VESSEL

Shape of Vessel	Ratio A/V	Maximum Pressure
Hemispherical	0.69	90.0
Cylindrical	1.24	84.0
Conical	1.34	83.0
L-shaped	1.62	75.0

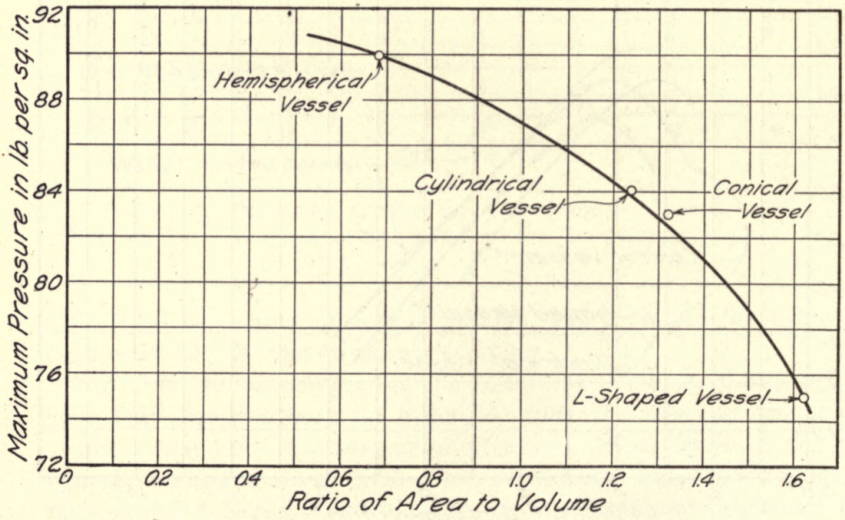


FIG. 20. CURVE SHOWING RELATION BETWEEN MAXIMUM PRESSURE AND RATIO OF AREA TO VOLUME OF VESSEL

The relation between maximum explosion pressure and the ratio of area to volume is shown in Fig. 20, which indicates that the cooling effect increases as the inside area increases.

21. *Rate of Cooling after Explosion.*—After the maximum pressure has been attained the enclosed gases in the explosion vessel start to cool. The cooling then continues at a rate which, if the combustion is complete and no after-burning takes place, is a function of (1) the air-gas ratio, (2) the character of the inside surface of the walls of the vessel, and (3) the ratio of inside wall surface to volume of the vessel. The curves in Fig. 21 show the rate of cooling for the products of combustion remaining in each of the vessels used, after the explosion of a mixture of 3 parts of air to 1 part of gas by volume. The initial temperature was chosen in each case as 2912 deg. F., and the curves were then constructed from the cooling curves on the indicator diagrams after allowance had been made for the contraction in volume due to the chemical reactions involved.

In Fig. 22 the drop in temperature from the initial value of 2912 deg. F. in 0.2 sec. and 0.5 sec. respectively after the time at which the gas was at the temperature of 2912 deg. F. has been plotted against the ratio of the area to the volume of the vessel. Since the volume was the same for all of the vessels, these curves indicate that the rate of cooling increases as the inside wall surface increases. If the nature of the inside surface is the same, it appears that the rate of cooling is a function of the area of the inside walls. The inside surface of the conical vessel was more polished and cleaner than the same surfaces for the other vessels. More radiant heat was therefore reflected from the walls of the conical vessel than from the walls of the others and the mixture cooled more slowly in the conical vessel. This may serve as an explanation for the fact that the point representing the drop in temperature in this vessel fell below the curve.

22. *Explosions of Hydrogen and Air.*—A mixture of one part of hydrogen to 2.4 parts of air by volume was exploded in the conical vessel in order to determine the relation between the maximum pressure and the time of explosion. This mixture contained the theoretical amount of oxygen necessary for the complete combustion of the hydrogen.

$$H_2 + \tfrac{1}{2}\, O_2 + 1.9\, N_2 \leftrightarrows H_2O + 1.9\, N_2$$

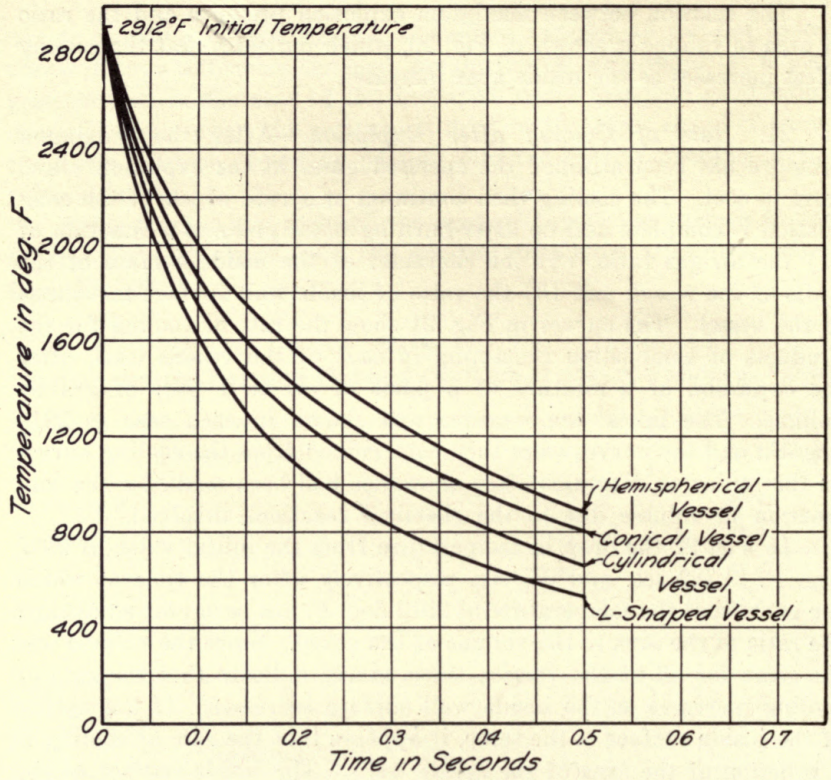


FIG. 21. RATE OF COOLING AFTER ATTAINMENT OF MAXIMUM PRESSURE

It was found that the time of explosion was greatly influenced by various conditions of turbulence and ignition, and these conditions were accordingly varied so that a wide range for the values of maximum pressures and times of explosion could be obtained. For some explosions the fan in the vessel was not run at any time. In other cases the fan was used during the admission, and in others during both the admission and the explosion. Ignition at times was accomplished by means of a single spark-gap at the vertex of the cone, and at other times by a chain of 6 spark-gaps in series extending down the axis of the vessel. These results are shown in Table 18.

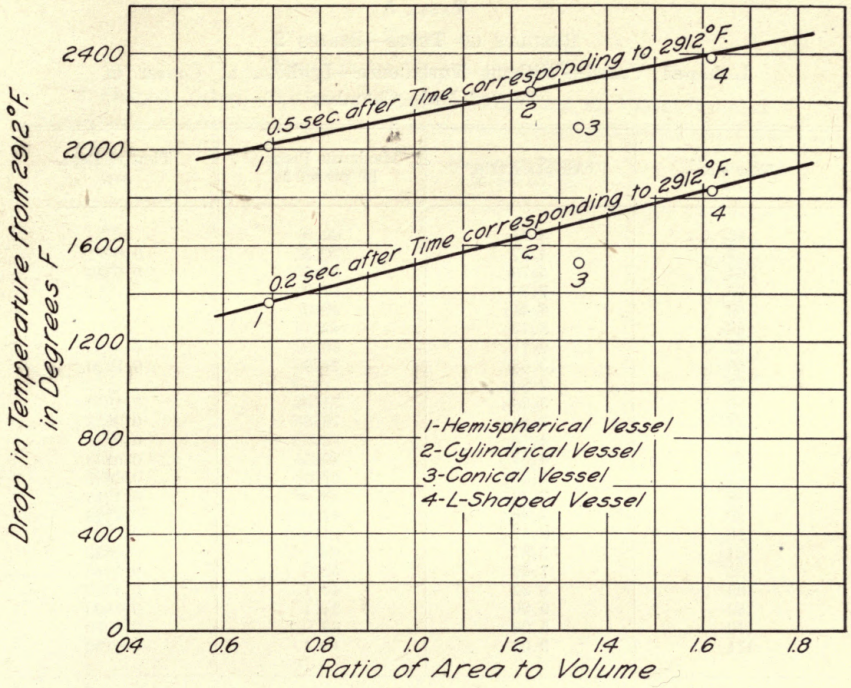


FIG. 22. CURVES SHOWING EFFECT OF AREA OF INSIDE WALLS OF VESSEL UPON RATE OF COOLING OF GAS

TABLE 4

RESULTS OF TESTS—SERIES 1

Cylindrical Vessel—Without Turbulence—Ignition at Center of Top

Test No.	Air-gas Ratio	Maximum Pressure lb. per sq. in.	Time of Expl. sec.
48	3.21	87.1	0.0510
49	3.77	92.5	0.0438
50	4.06	92.0	0.0366
51	4.99	84.1	0.0450
52	6.10	73.4	0.0668
53	7.03	66.2	0.0999
54	8.60	52.0	0.2390
55	9.43	44.5	0.4010
56	11.34	7.0	0.6280
57	3.62	86.5	0.0344
58	4.06	88.5	0.0370
59	4.59	87.5	0.0363

TABLE 5

RESULTS OF TESTS—SERIES 2

L-shaped Vessel—Without Turbulence—Ignition at Center of Top of Main Chamber

Test No.	Air-gas Ratio	Maximum Pressure lb. per sq. in.	Time of Expl. sec.
62	3.91	82.0	.....
63	4.97	76.5	0.0471
64	5.79	67.5	0.0549
65	7.25	57.0	.....
66	8.41	48.0	.....
66a	8.13	49.1	.....
67	9.71	36.5	0.3460
68	10.65	21.0	0.7220
82	2.83	....	.....
83	3.26	71.0	0.1830
84	3.64	78.8	0.0578
85	4.16	82.2	0.0381
86	4.87	80.5	0.0433
87	5.80	68.0	0.0637
88	7.17	57.0	0.1218
89	8.49	47.0	0.2163
90	10.57	21.0	0.7450
134	5.87	68.1	0.0623
135	7.52	52.5	0.1455
168	8.82	40.1	0.4230
169	9.99	21.1	0.7600
170	8.09	48.0	0.2070
171	9.03	40.1	0.4180

TABLE 6

RESULTS OF TESTS—SERIES 3

L-Shaped Vessel—With Turbulence—Ignition at Center of Top of Main Chamber

Test No.	Air-gas Ratio	Maximum Pressure lb. per sq. in.	Time of Expl. sec.
118	3.03	80.5	0.1265
119	3.31	83.2	0.0588
120	4.20	87.0	0.0223
121	4.66	88.0	0.0187
122	4.99	84.1	0.0204
123	6.11	74.1	0.0286
124	7.01	66.0	0.0371
125	8.23	59.0	.....
126	9.40	50.8	0.1057
127	10.27	48.1	0.1718
128	11.87	....	.....
129	8.39	59.0	0.0604
130	4.70	88.0	0.0178
132	11.00	....	.....
133	3.23	80.5	0.0702

TABLE 7

RESULTS OF TESTS—SERIES 4

L-Shaped Vessel—Without Turbulence—Ignition in Valve Chamber

Test No.	Air-gas Ratio	Maximum Pressure lb. per sq. in.	Time of Expl. sec.
69	3.18	61.5	0.0776
70	3.61	70.8	0.0557
71	4.06	71.0	0.0474
72	4.96	73.3	0.0504
73	5.68	66.1	0.0760
74	7.06	55.0	0.1455
75	9.26	41.5	0.3280
76	9.64	35.7	0.5100
77	10.81	12.6	0.7670
78	2.91	58.0	0.3790
79	4.14	72.5	0.0450
80	6.93	52.2	0.1179
82	4.04	74.4	0.0431
91	8.03	43.5	0.2970
92	9.12	36.5	0.4620
93	10.10	21.0	.....
94	10.20	22.1	0.8070
95	11.03	6.0	0.8860

TABLE 8

RESULTS OF TESTS—SERIES 5

L-shaped Vessel—With Turbulence—Ignition in Valve Chamber

Test No.	Air-gas Ratio	Maximum Pressure lb. per sq. in.	Time of Expl. sec.
136	3.06	74.1	0.0455
137	2.29	78.7	0.0347
138	4.14	84.2	0.0196
139	4.76	84.2	0.0204
140	5.05	85.2	0.0209
141	6.04	74.1	0.0272
142	7.35	65.3	0.0441
143	8.32	57.0	0.0528
144	9.46	51.5	0.0728
145	10.44	49.1	0.0973

TABLE 9

RESULTS OF TESTS—SERIES 6

L-Shaped Vessel—Without Turbulence—Ignition at Center of Top of Main Chamber and in Valve Chamber

Test No.	Air-gas Ratio	Maximum Pressure lb. per sq. in.	Time of Expl. sec.
146	3.05	74.1	0.0538
147	3.30	75.1	0.0502
148	4.05	76.2	0.0471
149	4.75	81.5	0.0453
150	5.13	74.1	0.0501
151	6.04	65.3	0.0705
152	7.13	53.5	0.1690
153	8.50	41.0	0.2940
154	9.22	35.7	0.4495
155	10.50	17.5	0.5890

TABLE 10

RESULTS OF TESTS—SERIES 7

L-Shaped Vessel—With Turbulence—Ignition at Center of Top of Main Chamber and in Valve Chamber

Test No.	Air-gas Ratio	Maximum Pressure lb. per sq. in.	Time of Expl. sec.
156	3.08	78.7	0.0532
157	3.49	85.1	0.0224
158	4.18	88.0	0.0151
159	4.78	87.0	0.0175
160	4.70	87.0	0.0222
161	5.20	83.2	0.0223
162	6.21	72.5	0.0343
163	7.07	65.2	0.0390
164	8.31	57.0	0.0548
165	9.28	51.5	0.0693
166	10.40	43.6	0.1482
167	11.14	19.5	0.2660

TABLE 11

RESULTS OF TESTS—SERIES 8

Cylindrical Vessel—Without Turbulence—Ignition at Center of Top

Test No.	Air-gas Ratio	Maximum Pressure lb. per sq. in.	Time of Expl. sec.
206	4.17	84.5	0.0300
209	5.29	75.5	0.0930
211	6.25	64.5	0.1150
212	8.33	43.5	0.4880
214	9.37	32.5	0.8320
215	11.47	....	.....
216	2.08	....	.....
217	3.65	81.0	.....
218	7.29	54.0	0.1720
219	2.61	67.5	0.1810
220	9.90	27.0	0.8060
221	3.65	80.0	0.0610
222	3.13	76.5	0.0580

TABLE 12

RESULTS OF TESTS—SERIES 9

Cylindrical Head—With Turbulence—Ignition at Center of Top

Test No.	Air-gas Ratio	Max. Press. lb. per sq. in.	Time of Expl. sec.
223	3.13	91.0	0.0460
225	4.17	92.0	0.0260
226	5.29	89.0	0.0330
227	6.25	78.5	0.0440
228	7.29	66.5	.....
230	9.37	49.0	0.1850
231	10.42	....	.....
232	11.47	....	.....
233	2.08	....	.....
234	2.61	83.5	0.1740
237	8.53	60.0	0.0930
238	9.90	....	.....

TABLE 13

RESULTS OF TESTS—SERIES 10

Conical Vessel—Without Turbulence—Ignition at Vertex

Test No.	Air-gas Ratio	Maximum Press. lb. per sq. in.	Time of Expl. sec.
274	3.13	83.6	0.0710
275	2.61	80.0	0.0950
276	4.17	78.0	0.0830
277	5.21	66.5	0.1390
278	6.25	54.3	0.3290
279	7.29	40.6	0.9420
280	8.33	....	.....

TABLE 14

RESULTS OF TESTS—SERIES 11

Conical Vessel—With Turbulence—Ignition at Vertex

Test No.	Air-gas Ratio	Maximum Press. lb. per sq. in.	Time of Expl. sec.
329	2.08	87.0	0.0700
330	2.61	91.5	0.0280
331	3.13	93.8	0.0390
332	3.65	90.3	0.0380
333	4.17	83.6	0.0516
334	5.21	75.5	0.0496
335	6.25	66.6	0.0810
336	7.29	56.5	0.1360
337	8.33	46.3	0.3440

TABLE 15

RESULTS OF TESTS—SERIES 12

Conical Vessel—Without Turbulence—Ignition 3 in. below Vertex

Test No.	Air-gas Ratio	Maximum Press. lb. per sq. in.	Time of Expl. sec.
306	2.61	78.0	0.0400
307	4.17	73.5	0.0790
308	5.13	81.6	0.0560
310	5.21	65.5	0.1320
311	6.25	53.5	0.2710
312	7.29	41.2	0.5500
313	8.33	....	.....
314	2.08	60.0	0.1360
315	7.81	7.0	.....

TABLE 16

RESULTS OF TESTS—SERIES 13

Conical Vessel—With Turbulence—Ignition 3 in. below Vertex

Test No.	Air-gas Ratio	Maximum Pressure lb. per sq. in.	Time of Expl. sec.
316	2.08	80.3	0.0880
317	2.61	91.5	0.0440
318	3.13	93.8	0.0360
319	3.65	91.5	0.0380
320	4.17	87.0	0.0340
323	7.29	59.5	0.1190
324	7.81	52.0	0.1670
325	8.85	44.8	0.2670
326	9.37	5.0	.....
327	5.21	79.0	0.0640
328	6.25	68.0	0.0880

TABLE 17

RESULTS OF TESTS—SERIES 14

Hemispherical Vessel—Without Turbulence—Ignition at Top

Test No.	Air-gas Ratio	Maximum Pressure lb. per sq. in.	Time of Expl. sec.
350	3.14	89.0	0.0391
351	4.20	90.5	0.0465
352	5.18	77.5	0.0732
353	6.25	66.2	0.1330
354	7.05	57.8	0.2040
355	8.22	47.2	0.4340
356	9.32	17.0	.....
357	2.47	....	.....
358	4.39	85.0	0.0442
359	5.76	88.6	0.0329
360	2.88	84.0	0.0625

TABLE 18

RESULTS OF EXPLOSIONS OF MIXTURE OF 1.0 PART HYDROGEN TO 2.4 PARTS AIR

Test No.	Turbulence	Ignition	Max. Pressure lb. per sq. in.	Time of Expl. sec.
1 H	During Admission	At Vertex	75.0	0.0175
2 H	During Explosion	At Vertex	78.0	0.0146
4 H	During Admission	At Vertex	86.0	0.0098
5 H	During Admission	6-gap	77.0	0.0161
25 H	During Explosion	6-gap	82.5	0.0126
26 H	None	At Vertex	84.8	0.0095
27 H	During Admission	At Vertex	79.2	0.0148

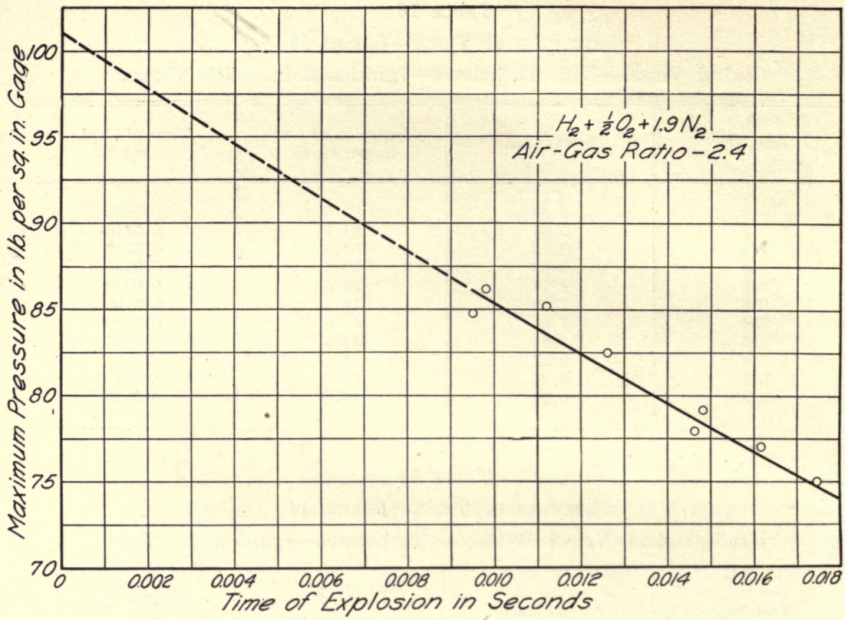


FIG. 23. MAXIMUM PRESSURE-TIME CURVE FOR EXPLOSIONS OF HYDROGEN AND AIR

Fig. 23 shows the relation between the maximum pressure and time of explosion. The relation seems to be practically linear. The variations in maximum pressures are due to variations in the heat loss to the walls of the vessel. The latter is a function of the time of explosion. If the curve is extended, as shown by the dotted portion in Fig. 23, the intercept on the zero-time ordinate represents the maximum pressure that would be produced by an adiabatic explosion of the same mixture. The maximum pressure for an adiabatic explosion has been computed in Appendix A. The computed value of 101 lb. per sq. in. gage agrees with the value of 101 lb. per sq. in. shown in Fig. 23. In Appendix A maximum pressures have also been computed for this same mixture on the assumption of heat losses ranging from 5 to 25 per cent. These results have been plotted in Fig. 24, which shows the relation between maximum pressures and heat lost

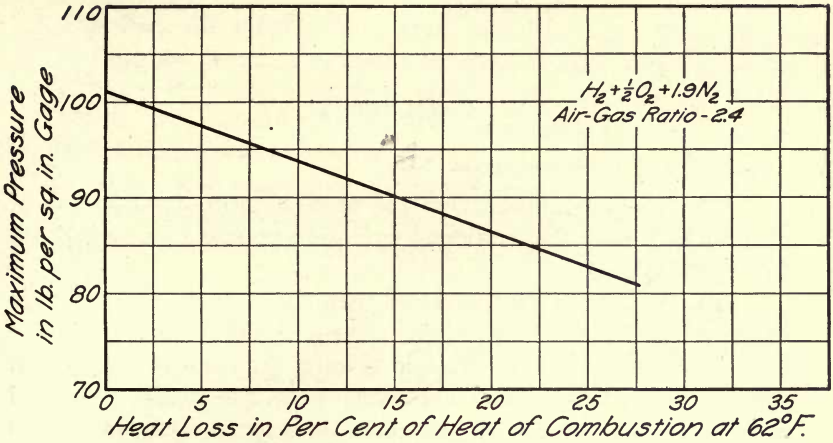


FIG. 24. THEORETICAL MAXIMUM PRESSURE AND HEAT LOSS FOR EXPLOSIONS OF HYDROGEN AND AIR

to the walls of the vessel. The highest maximum pressure observed was 86.0 lb. per sq. in. gage, and occurred on test 4H for which the time of explosion was 0.0098 sec. Reference to Fig. 24 shows a loss of 20.8 per cent of the heat of combustion of the gas charge at 62 deg. F. and 29.92 in. mercury for this maximum pressure.

The results obtained by W. T. David[211] indicate that the loss of heat by *radiation* during the explosion of a 25.4 per cent mixture of hydrogen and air is about 0.5 per cent of the heat of combustion, but he gives no estimate of the loss of heat by *conduction* to the walls of the vessel. The explosion vessel used by David, however, had a volume of about 1045 cu. in. while the one used in this investigation had a volume of 155 cu. in.; therefore the cooling effect of the walls of the vessel would be much more marked in the latter case than in the former. Moreover, the very close proximity of the walls of the conical vessel to the ignition point, which was at the vertex of the cone, would tend to cause an excessive heat loss at the beginning of the explosion. The presence of a film of water remaining on the walls of the vessel from a previous explosion would also augment the heat loss. Taking all these things into consideration, the heat loss of 20.8 per cent does not appear unreasonable for the comparatively small conical vessel.

V. Conclusions

23. *Summary of Conclusions.*—

(1) For the illuminating gas used, a ratio of air to gas of about 4 to 1 gives the maximum explosion pressure and minimum time for explosion.

(2) In general, the effect of turbulence during explosion is to cause an increase of maximum pressure and a decrease in the time of explosion. This effect is greater for lean mixtures than for the richer ones. The maximum pressure is also produced with a slightly greater air-gas ratio than for the case where no turbulence exists.

(3) The effect of turbulence seems to be due to the more intimate mixing of the gas and air before inflammation, thus bringing more molecules into contact, rather than to the projection of the flame into the unburned parts of the gas mixture.

(4) The position of the source of ignition has a considerable influence on the rate of inflammation and on the maximum pressure. In vessels patterned after the L-head type of combustion space used in internal combustion engines, ignition in the valve chamber results in a maximum pressure of about 10 per cent less than that obtained when ignition occurs at the center of the head.

(5) Both turbulence and variations in the position of ignition seem to have more influence upon the rate of inflammation than upon the maximum pressure. An explanation for this is given in Section IV, page 25.

(6) In certain cases there is some evidence of the formation of pressure waves which travel smoothly through the mixture and produce a higher maximum pressure than if the inflammation had proceeded in the usual way. These pressure waves differ in character from true explosion waves.

(7) The maximum pressure and time of explosion are materially affected by the shape of the explosion vessel. This seems to be caused by variations in the ratio of surface to volume for the different vessels. From the standpoint of maximum pressure

produced, the spherical explosion vessel is best. The cylindrical and conical vessels give about the same results, but the maximum pressure is about 8 per cent lower than that for the spherical vessel. The L-head type gives results about 16.5 per cent lower than the spherical.

(8) The combustion of the gases in any pocket in the vessel is more or less incomplete, due to the cooling effect of the walls. The incomplete combustion results in a reduction of the maximum pressure.

(9) The cooling of the gases for a given mixture during any time after the attainment of maximum pressure varies directly with the ratio of surface to volume of the explosion vessel, for the particular vessels used.

(10) Radiation from the gaseous mass is an important factor in the cooling of the mixture. Variations in the character of the inner surface of the walls of the vessel cause variations in the cooling curves.

(11) The experimental results for the maximum pressures produced by explosions of hydrogen and air agree very closely with the values computed from the properties of the gas mixture.

APPENDIX A

Calculation of Maximum Explosion Pressures of Mixtures of Hydrogen and Air

1. *Discussion of Equations.*—In order to calculate the maximum pressures produced in the explosion of any inflammable gas mixture, three factors must be taken into consideration:

(1) The heat of combustion of the mixture.

(2) The variation of the specific heats of the gases.

(3) The dissociation of the products of combustion, or rather the incomplete burning of the gases due to partially attained equilibrium at the high temperatures.

The mixture is assumed to be in a state of chemical equilibrium at the instant of maximum pressure.

The following notation will be used in the calculations:

T_1 = the temperature at equilibrium, deg. F. abs.
T_2 = initial temperature, deg. F. abs.
x = the progress of the reaction (= 1 at completion).
m = initial mixture, mols.
m' = mixture at equilibrium, mols.
U_2 = total thermal energy of the mixture at T_2, B.t.u. per mol.
U_1 = total thermal energy of the mixture at T_1, B.t.u. per mol.
u_2' = thermal energy of hydrogen at T_2, B.t.u. per mol.
u_2 = thermal energy of other diatomic gases at T_2, B.t.u. per mol.
u'_1 = thermal energy of hydrogen at T_1, B.t.u. per mol.
u_1 = thermal energy of other diatomic gases at T_1, B.t.u. per mol.
K_p = equilibrium constant.
H_v = lower heating value of the mixture at T_2, at constant volume, B.t.u. per mol.

In order to determine the two unknown variables x and T_2, two independent equations must be employed.*

* Credit is due to G. A. Goodenough, Professor of Thermodynamics at the University of Illinois, for the development of this method of analysis.

Equating the energies of the mixture before explosion and at the time of equilibrium (since the process is adiabatic and at constant volume),

$$U_1 + xH_v = U_2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

$$x = \frac{U_2 - U_1}{Hv} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

Then for a mixture of one part of hydrogen to 2.4 parts of air

$$x = \frac{2.4u'_2 + u_2 - (2.4u'_1 + u_1)}{Hv} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

By substituting values of T, corresponding values of x may be calculated.

The equilibrium constant K_p is a function of the temperature T and of x. It is defined in the hydrogen reaction as

$$K_p = \frac{P_{H_2O}}{P_{H_2} \cdot (P_{O_2})^{\frac{1}{2}}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

where P denotes the partial pressures of the various constituents as denoted by the subscripts. The following expression for K_p in terms of T has been derived from the results of a number of investigators:

$$4.571 \log K_p = \frac{102\,100}{T} - 6.2331 \log T_2 + 0.000236\, T_2 + 0.0333 \cdot 10^{-6}\, T_2^2 + 1.1 \quad . \quad . \quad . \quad (5)$$

2. *Calculations for Mixture* $H_2 + \frac{1}{2}\, O_2 + 1.9\, N_2$.—The expression for K_p in terms of partial pressures is transformed into an expression in terms of the variable x as follows. From the reaction equation

$$H_2 + \tfrac{1}{2}\, O_2 + 1.9\, N_2 = H_2O + 1.9\, N_2$$

the initial mixture and the mixture at equilibrium are

Initial	At equilibrium
H_2....1.0 mol.	H_2O.....x mol.
O_2....0.5 mol.	H_2....$(1-x)$ mol.
N_2....1.9 mol.	O_2.....$0.5x$ mol.
	N_2.....1.9 mol.
m.....3.4 mol.	m'..$m - 0.5x$ mol.

In the equilibrium mixture the partial pressures are

$$P_{H_2O} = \frac{x}{m'} P$$

$$P_{H_2} = \frac{1-x}{m'} P$$

$$P_{O_2} = \frac{0.5x}{m'} P$$

where P denotes the total pressure of the mixture.

Substituting in equation (4)

$$K_p = \left(\frac{x}{1-x}\sqrt{\frac{m'}{0.5x}}\right)\frac{1}{\sqrt{P}} \quad \ldots\ldots\ldots \quad (6)$$

The volume remains constant; therefore the total pressure P is variable. To eliminate P combine the two equations

$$P_1 V = mRT_1 \text{ and } PV = m'RT$$

giving $\dfrac{P_1}{P} = \dfrac{mT_1}{m'T}$ *or* $\dfrac{1}{\sqrt{P}} = \dfrac{1}{\sqrt{P_1}}\sqrt{\dfrac{m}{m'}}\sqrt{\dfrac{T_1}{T}}$

Thus equation (6) becomes

$$K_p = \frac{x}{1-x}\sqrt{\frac{m}{0.5x}}\frac{1}{\sqrt{P_1}}\sqrt{\frac{T_1}{T}} \quad \ldots\ldots\ldots \quad (7)$$

Taking $T = T_2$ at equilibrium and $m = 3.4$, this equation may be written

$$\log K_p = \log\frac{x}{1-x} - \tfrac{1}{2}\log\frac{6.8}{x} - \tfrac{1}{2}\log P_1 - \tfrac{1}{2}\log\frac{T_2}{T_1} \quad (8)$$

The elimination of $\log K_p$ between equations (5) and (6) gives a second relation between x and T.

The constant 1.1 in equation (5) is based upon the atmosphere as the unit of pressure; hence, since P_1 is one atmosphere, the term $\frac{1}{2}\log P_1$ in equation (8) vanishes.

Substitution of values for T_2 in the energy equation (3) gives

T_2....	4200	4400	4600	4800	5000
x.....	0.721	0.772	0.827	0.884	0.945

Substitution of values for T_2 in the equilibrium equation gives

T_2....	4000	4400	4800	5000
x.....	0.988	0.975	0.954	0.939

These two sets of values have been plotted in Fig. 25. Reference to that figure shows that the intersection of the two curves gives values for T_2 of 4985 deg. F. abs., and for x, of 0.940, satisfying both equations.

The maximum pressure is found from the gas laws given above:

$$P_2 = \frac{m - \frac{1}{2}x}{m} \frac{T_2}{T_1} P_1 = \frac{(3.4 - 0.5 \times 0.940) \times 4985 \times 14.4}{3.4 \times 535}$$

$$= 115.5 \text{ lb. per sq. in. abs.}$$
$$= 101.1 \text{ lb. per sq. in. gage.}$$

An initial temperature of 75 deg. F. and an initial pressure of 14.4 lb. per sq. in. abs. have been assumed.

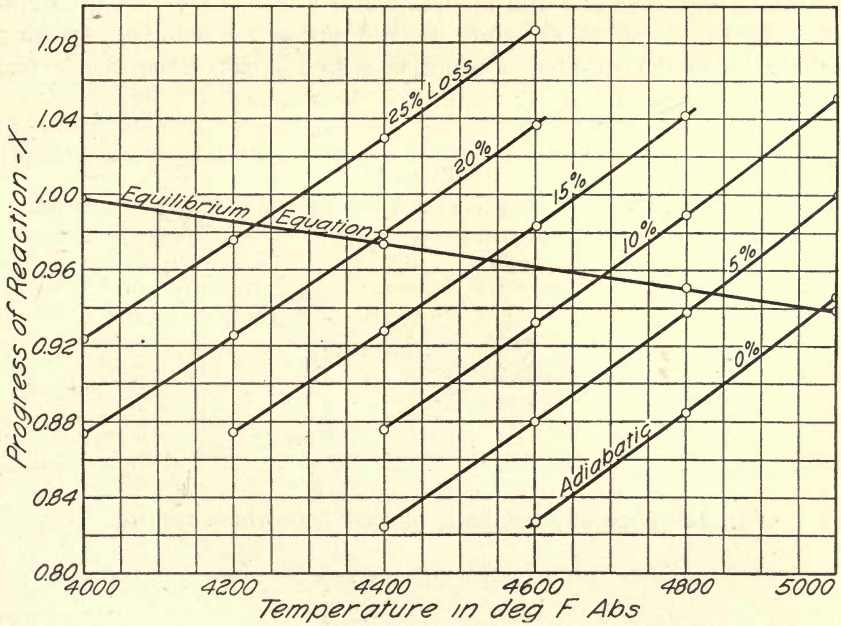


FIG. 25. GRAPHICAL SOLUTION FOR ENERGY AND EQUILIBRIUM EQUATIONS

If an amount of heat h is assumed to be lost to the walls of the vessel during explosion, the energy equation will be modified as follows:

$$U_1 + xH_v = U_2 + h$$

or
$$x = \frac{U_2 - U_1 + h}{H_v} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (9)$$

The equilibrium equation is not affected by the heat loss.

The following amounts of heat loss, expressed in per cent of the heat of combustion of the mixture at 62 deg. F. (102 930 B.t.u.) have been assumed.

	B.t.u.
5 per cent	5 147
10 per cent	10 293
15 per cent	15 440
20 per cent	20 586
25 per cent	25 733

Adding these amounts into the numerator of the energy equation and solving for x and T_2 as before, several curves are obtained, crossing the curve of the equilibrium equation as in Fig. 25. From the several intersections the following results may be obtained:

TABLE 19

THEORETICAL MAXIMUM PRESSURES FOR EXPLOSIONS OF HYDROGEN AND AIR

Heat Loss Per Cent	T_2 deg. F. abs.	x	P_2 lb. per sq. in. gage
0	4985	0.940	101.1
5	4836	0.949	97.3
10	4688	0.957	93.9
15	4540	0.966	90.6
20	4387	0.974	86.6
25	4228	0.984	82.8

Fig. 24 (page 49) has been plotted from these results.

APPENDIX B

Historical Review of Principal Researches

1. *Researches of Dugald Clerk.*—In 1884 Dugald Clerk[31*] exploded mixtures of Cambridge coal gas and air at various initial pressures and temperatures, making use of a cylindrical explosion vessel having a volume of 317 cu. in. Explosions of hydrogen and air were also made in the same apparatus. The pressure developed by the explosion was measured by means of a Richards steam engine indicator and the pressure diagrams were traced on a revolving drum. The mixture was ignited by a spark plug placed at the bottom of the cylinder.

In a later series of tests a cylinder of 7 in. diameter and length was used. In place of the drum used on the Richards indicator a longitudinally moving slide was substituted and the recording paper was fastened to the slide. The speed of the slide was determined by means of an electrically driven tuning fork which traced a curve on the recording paper.

A set of explosion curves for different air-gas ratios, taken with Clerk's later apparatus, is shown in Fig. 26, and curves showing the

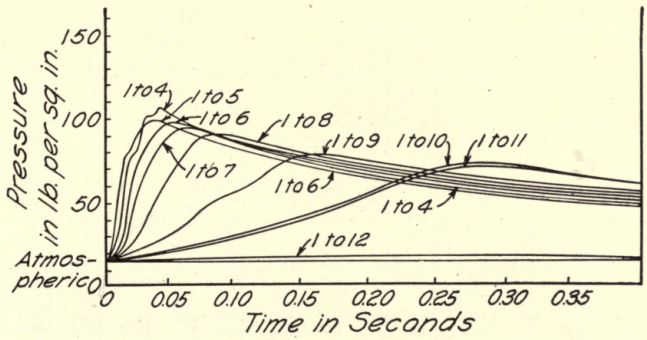


Fig. 26. Explosion Records for Coal Gas and Air—Dugald Clerk

* The small figures used in this section refer to the reference numbers given in the Bibliography in Appendix C.

relation between maximum pressure and time and the air-gas ratio are shown in Fig. 27. The latter are typical of the curves obtained by all the investigators in this field.

Clerk's results are subject to the criticism that a piston indicator has too much inertia to record rapid changes in pressure with a high degree of accuracy. His results, however, are probably more complete and accurate than any of the other early investigators.

2. *Researches of Grover.*—In 1895 F. Grover[132] made some experiments on the explosions of mixtures of coal-gas and air. His apparatus was similar to that used by Clerk except that the explosion

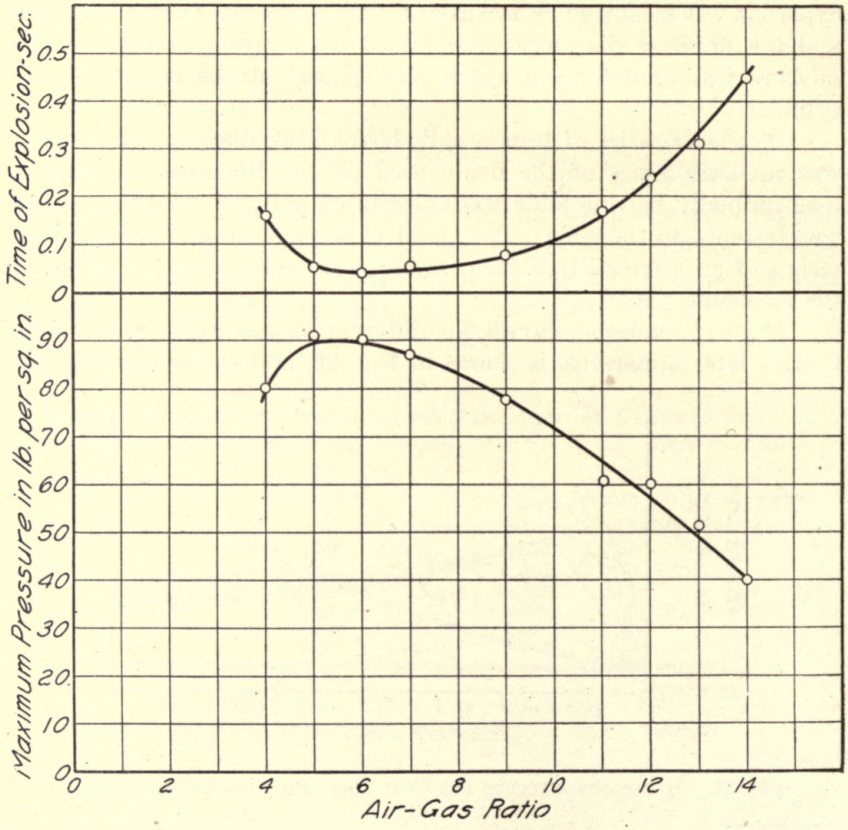


FIG. 27. EXPLOSION CURVES FOR COAL GAS AND AIR—DUGALD CLERK

vessel had a volume of 1 cu. ft. The cylinder was 8 in. in diameter and 34 in. long. The gases were introduced by filling the cylinder with water and allowing the mixture to enter as the water was withdrawn.

Grover's curves showing the relation between maximum pressure and air-gas ratio give lower values than those obtained by Clerk, and later at the Massachusetts Institute of Technology, although the calorific value of the gases used was practically the same for all cases. He attributes this difference to a reduction in the sensible heat due to the heat used in evaporating the water adhering to the cylinder walls after the gas charge had been drawn in. It is more probable, however, that the effect was due to faulty mixing of the gas charge. The time of explosion as determined by Grover was less than that found by the other experimenters. This, together with the fact that a lean mixture can be burned much more rapidly if a relatively strong mixture is situated in the immediate vicinity of the ignition point, leads to the conclusion that the lower pressures developed were caused by incomplete mixture.

Grover also studied the effect of diluting the air-gas charge with the products of combustion left from the preceding explosion. His results seemed to indicate that the presence of from 5 to 30 per cent of the exhaust gas raised the pressure as much as 19 lb. per sq. in.

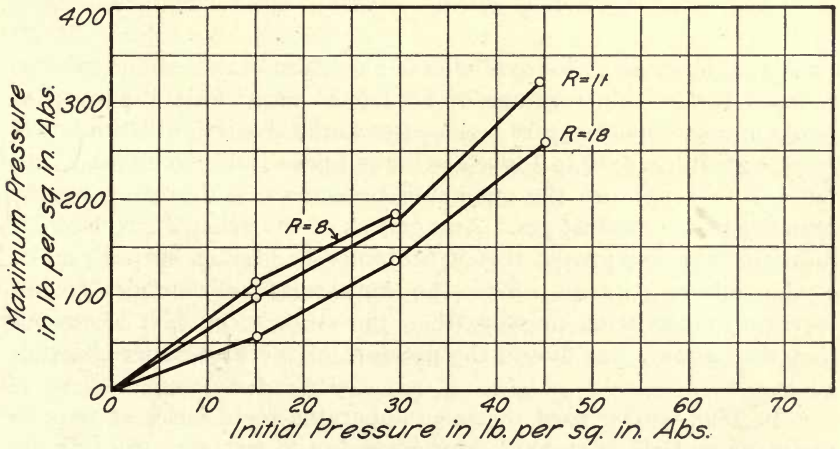


FIG. 28. EFFECT OF INITIAL PRESSURE ON MAXIMUM PRESSURE FOR MIXTURES OF ACETYLENE AND AIR—GROVER

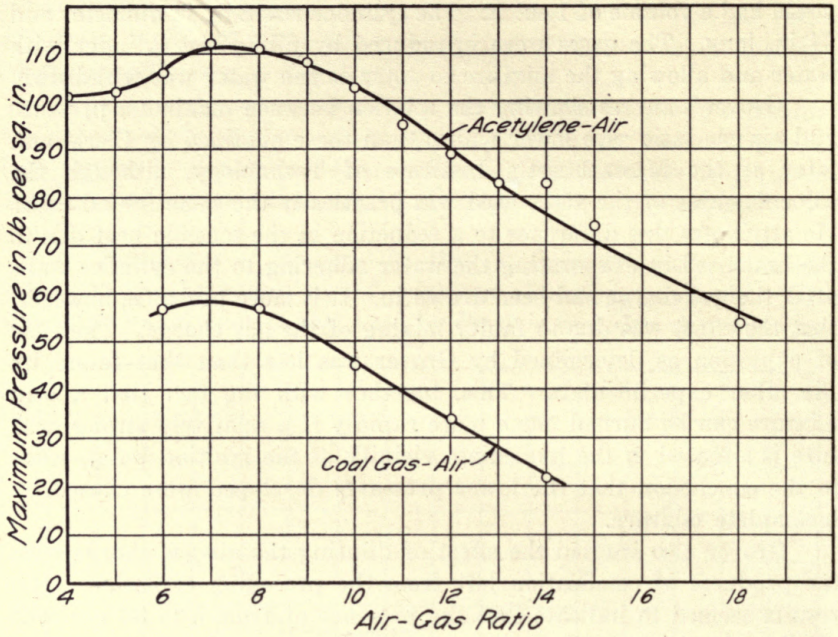


FIG. 29. EXPLOSION CURVES FOR MIXTURES OF ACETYLENE AND AIR, AND COAL GAS AND AIR—GROVER

above that observed in the explosion of a mixture containing no exhaust gas and the same percentage of fresh coal gas. This apparent increase of maximum pressure became less as the strength of the mixture became greater. A 12 to 1 mixture showed practically no increase, and for a 7 to 1 mixture the maximum pressure was decreased by the presence of the exhaust gas. An analysis of the exhaust gas used for dilution, however, proved that it contained as high as 30 per cent of combustible constituents. Since the leaner mixtures showed a greater increase in maximum pressure than the stronger ones, it is obvious that the increase was due to the presence of these added combustible gases.

In 1898 Grover used the same apparatus for a series of tests on acetylene and air mixtures. Any error due to water on the cylinder walls was eliminated by measuring the gas into the cylinder from a gas holder. Initial pressures of 1,2, and 3 atmospheres were used for

mixtures of acetylene and air and for coal-gas and air. The results of the coal-gas and air tests were again low as compared with Clerk's, thus indicating the lack of a perfectly homogeneous mixture.

Curves showing the relation between explosion pressure and initial pressure are shown in Fig. 28, and others showing the relation between explosion pressure and air-gas ratio are shown in Fig. 29. In Fig. 28 the deviation from the straight-line law found by other investigators may be explained by the evidence of faulty mixing to be found in all of Grover's work.

3. *Researches at the Massachusetts Institute of Technology.*—In 1898 a series of experiments on explosions of gaseous mixtures was made at the Massachusetts Institute of Technology.[132] The apparatus used differed from Clerk's only in the recording device. A rotating disc was substituted for the slide used by Clerk, thus giving pressure curves on polar instead of rectangular coördinates. The investigation was extended to include mixtures of gasoline vapor and air. Otherwise they duplicate the results obtained by Clerk.

4. *Researches of Petavel.*—J. E. Petavel's[91] experiments in 1902 are of interest inasmuch as they are the only ones in which very high initial pressures were used. The explosion vessel was a spherical steel bomb having an internal diameter of 4 in. and a volume of 0.0195 cu. ft. The spring of the indicator consisted of a steel tube ending in a piston and loaded as a hollow column. The motion was magnified by means of a system of levers and a mirror. Since the instrument was practically free from inertia effects, it was a great improvement on the ones used by previous investigators, and was able to follow the rapid variations in pressure without appreciable lag.

5. *Researches of Bairstow and Horsely.*—In 1902 L. Bairstow and E. C. Horsely[75] experimented on different explosive mixtures, making use of the apparatus later used by Bairstow and Alexander. Their results indicate that the ratio of explosion pressure to initial pressure increases slightly with the increase in initial pressure.

6. *Researches of Bairstow and Alexander.*—In 1905 L. Bairstow and A. Alexander[90] experimented upon mixtures of coal gas and air. The gas used was city illuminating gas with an average heating value

of 628 B.t.u. per cu. ft. The explosion vessel was a cylinder 10 in. in diameter and 18 in. long. The indicator was a Simplex steam engine indicator and was, therefore, subject to the criticism that it has too much inertia.

It was found that mixtures could be allowed to stand as long as 17 hours without becoming homogeneous, and in order to overcome this difficulty they made use of a mixing plate operated by hand. Ignition was accomplished by means of a high tension spark through a firing tube. This tube which was pierced with small holes extended down into the explosion vessel. All holes were closed except the one located at the point where ignition was desired. When the spark was passed at the top of the tube, the mixture contained within the tube exploded and threw a jet of flame through the open hole, thus igniting the contents of the explosion vessel. In this way ignition at any desired point within the vessel was obtained. This method did not afford a constant intensity of ignition. When the lower holes were opened, the explosion in the tube projected the jet of flame farther into the vessel than it did when the upper holes were opened. The distance also varied with the mixture in the tube. Consequently some

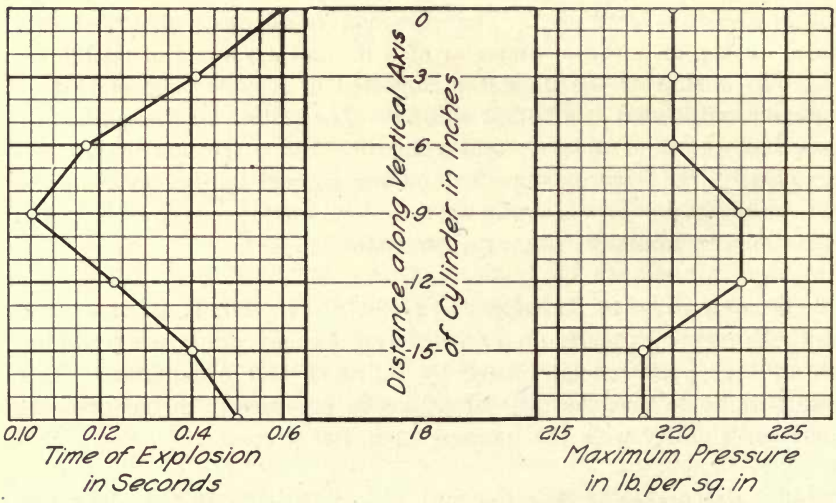


Fig. 30. Effect of Position of Ignition on Maximum Pressure and Time of Explosion—Bairstow and Alexander

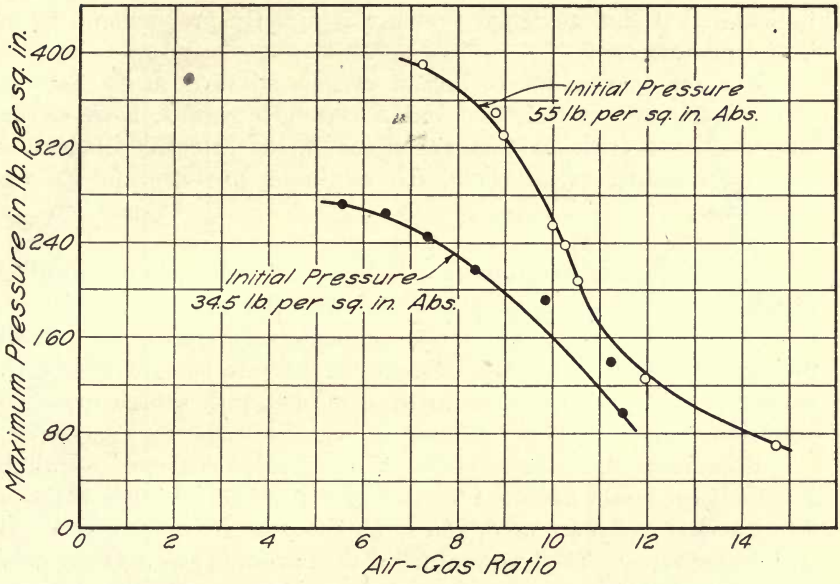


FIG. 31. EFFECT OF STRENGTH OF MIXTURE AND OF INITIAL PRESSURE ON MAXIMUM PRESSURE—BAIRSTOW AND ALEXANDER

variation in the maximum pressures and times of explosion were caused by variations in the intensity of ignition.

Fig. 30 shows the effect of the position of the ignition point upon the maximum pressure for a 7 to 1 mixture with an initial pressure of 35 lb. per sq. in. absolute. Similar tests were made with a weaker mixture, and the position of the ignition point for most rapid combustion was found to be about 3 in. below the center of the vessel. This can be attributed to the fact that the convection currents in the weaker mixture have velocity sufficient to be comparable with the rate of inflammation, and the position of the ignition point in the lower part of the vessel allows the action of the convection currents to become effective.

Two series of tests were made with varying mixtures, in all cases using four electric sparks in series passing through the axis of the explosion vessel. For one series an initial pressure of 55 lb. per sq. in. absolute, and for the other an initial pressure of 34.5 lb. per sq. in. absolute was used. The results are shown in Fig. 31. Fig. 32 clearly

indicates that the maximum pressure is directly proportional to the initial pressure.

Further data on the cooling of various mixtures after explosion were given. All of Bairstow and Alexander's results, however, are subject to the criticism that variations in the intensity of ignition may have caused variations in the maximum pressure and time of explosion.

7. *Researches of Hopkinson.*—The work of B. Hopkinson[97] is distinctly significant inasmuch as he was the first investigator to make extensive use of an optical indicator for recording the explosion pressure. With this instrument he was able to record the rapid variations of pressure during explosion with a high degree of precision.

Hopkinson exploded mixtures of Cambridge coal-gas and air in a cylindrical vessel having a volume of 6.2 cu. ft. Air-gas ratios of 9 to 1 and 12 to 1 were used, and in all cases the gases were saturated with water vapor. The temperature of the burning gases was measured by means of platinum resistance thermometers inserted at different parts of the vessel as shown in Fig. 33. These thermometers consisted of short coils of platinum wire 0.001 in. in diameter. They were

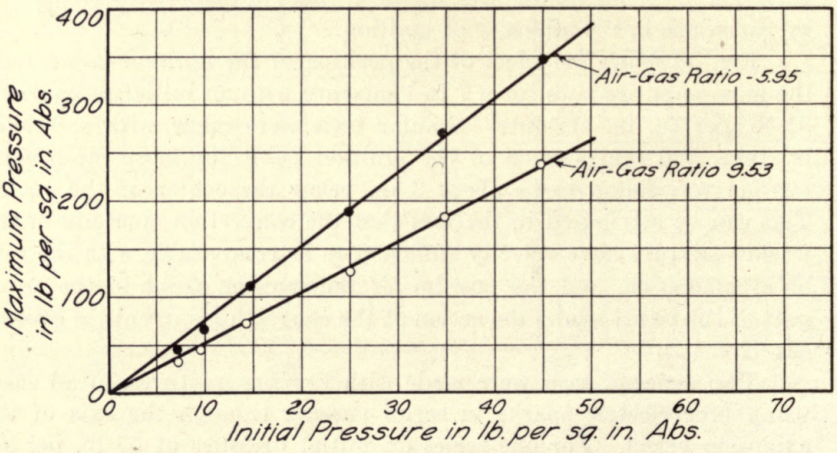


FIG. 32. EFFECT OF INITIAL PRESSURE ON MAXIMUM PRESSURE—BAIRSTOW AND ALEXANDER

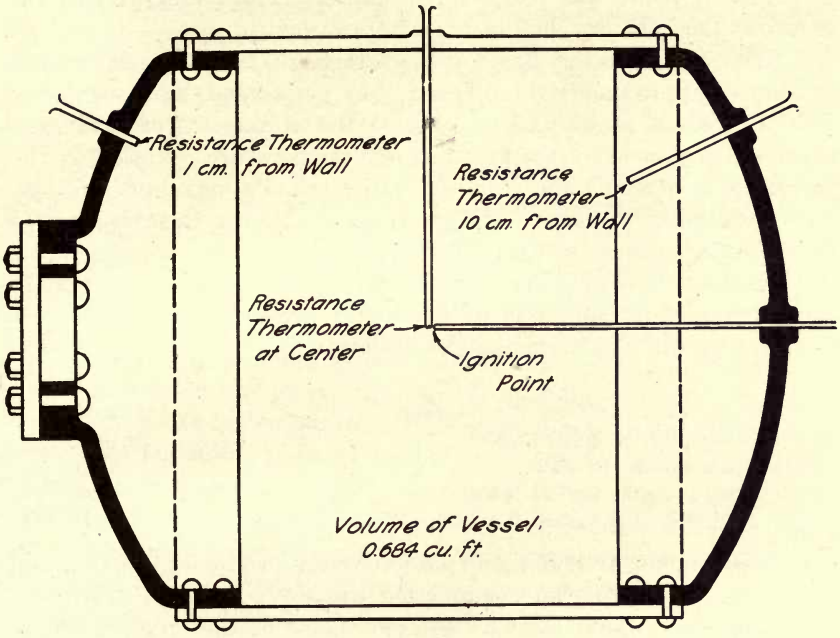


FIG. 33. EXPLOSION VESSEL—HOPKINSON

connected in series with a galvanometer, and a change in resistance of the coils, due to a change in temperature, caused a variation in the current in the circuit, thus deflecting the mirror on the galvanometer. Records of both temperatures and pressures were made by beams of light reflected from mirrors on the galvanometer and indicator to a photographic film fastened on a revolving drum. A correction was made for the time lag of the thermometers.

When the charge was fired, it was found that the coil placed at the center of the vessel almost invariably melted, thus indicating that the temperature was at least as high as 1755 deg. C. The curves in Fig. 34 showing the relation between temperature at the center of the vessel, maximum pressure, and time elapsed from ignition, also show that the center coil melted about 0.025 sec. before the attainment of maximum pressure. The temperature at the beginning of inflammation rose rapidly, indicating that the combustion of the mass of gas near

the ignition point was practically complete before the pressure, as shown by the indicator, had increased appreciably.

After ignition the flame spread through the mixture with a velocity of approximately 150 centimeters per second, and completely filled the vessel about 0.03 sec. before the attainment of maximum pressure, as proved by the fact that the temperature recorded by the thermometer placed 1 cm. from the wall reached a maximum 0.03 sec. before maximum pressure. The gas at the center was then compressed adiabatically to a temperature considerably above the melting point of platinum. It is probable that this temperature was approximately 1900 deg. C. At the time of maximum pressure the temperature distribution was approximately as follows:

	Deg. C.
Mean, calculated from the pressure	1600
Center, near the ignition point	1900
10 cm. within the wall	1700
1 cm. from the wall at the end	1200
1 cm. from the wall at the side	850

It is evident, even if the explosion vessel was nonconducting and the effect of radiation and conduction was excluded, that differences in temperature would exist at different parts of the mixture due to variations in the degree of compression at the respective points.

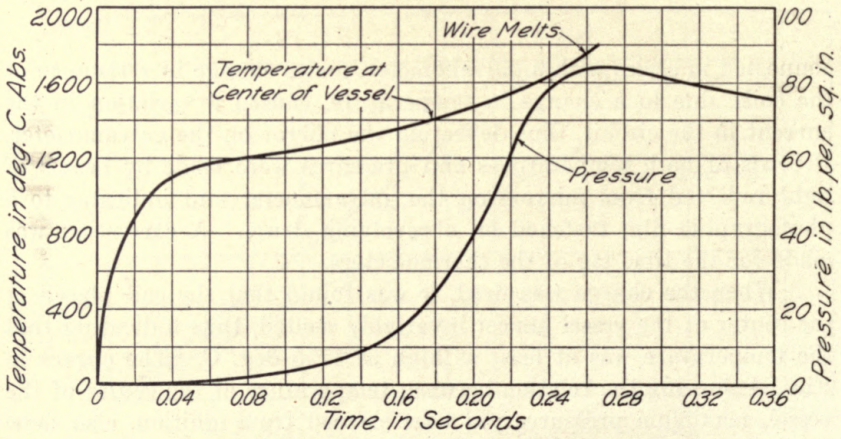


FIG. 34. EXPLOSION CURVES FOR MIXTURES OF CAMBRIDGE COAL GAS AND AIR—HOPKINSON

At a time 0.05 sec. later than the attainment of maximum pressure, the mean temperature of the gas calculated from the pressure was about 1100 deg. C. A value of 1160 deg. C. was determined experimentally by making use of a platinum resistance wire stretched entirely across the vessel.

In the explosion of 12 to 1 mixtures the effect of convection became more important because the flame was propagated more slowly. The temperature of the gas immediately below the ignition point at first increased, and then decreased, due to the upward movement of the cold unburned gases as they followed the ascending flame. At a time one second later than ignition the pressure was still less than 10 lb. per sq. in. and the upper half of the vessel was filled with burned gas which was giving up heat to the cylinder walls. The last portions of gas to be ignited were those immediately below the ignition point. The maximum pressure was 50 lb. per sq. in. and was attained 2.5 sec. after ignition. During that time at least one half of the superficial area of the vessel had been in contact with the flame. The loss of heat before the attainment of maximum pressure was, therefore, greater for a weak mixture than for a stronger one.

A later investigation[115] was undertaken with the object of measuring the heat loss to the walls of the cylinder. The explosion vessel was a cast iron cylinder one foot in diameter and one foot long, and was lined with wood. The wood was overlaid with a continuous grid of strip copper, 0.25 in. wide and 0.04 in. thick, which was connected in series with a galvanometer in order to serve as a resistance thermometer. A Hopkinson optical indicator was used to measure the pressure, and both records were photographed on a film.

The results of this series of experiments are shown in Fig. 35. Concerning these results Hopkinson says: "The heat loss begins about 0.05 seconds after ignition, when the flame first comes in contact with the copper. At first the loss goes on at a very great rate, and by the time the maximum pressure is reached, about 1700 calories, or 12 per cent of the gross heating value of the gas, has passed to the walls. The rate of heat loss at this point is about 10 calories per square centimeter per second, and the mean gas temperature is 1760 degrees Centigrade. At 0.2 seconds from ignition the rate of heat loss is about 3.5 calories per square centimeter per second, and the mean gas temperature is 1300 degrees Centigrade. This mean temperature

is reduced in the ratio $\frac{74}{100}$ between these two points, but the rate of heat loss at 0.2 seconds is only one third of what it was at maximum pressure.''

Hopkinson's results, obtained from these experiments, doubtless included some of the radiation loss together with the loss due to conduction. In Clerk's opinion only the conduction loss is included, but even the highly polished surface does not reflect all radiation, and the metal strip would necessarily be raised in temperatue by the radiation received.

8. *Researches of Nagel.*—In 1908 A. Nagel[128] conducted an elaborate investigation on the velocity of inflammation of various gaseous mixtures. The explosion vessel used was a spherical steel bomb 40 cm. in diameter. A diaphragm in communication with the bomb, and connected mechanically to a concave mirror, indicated the pressure developed by the explosion. Ignition was accomplished by means of

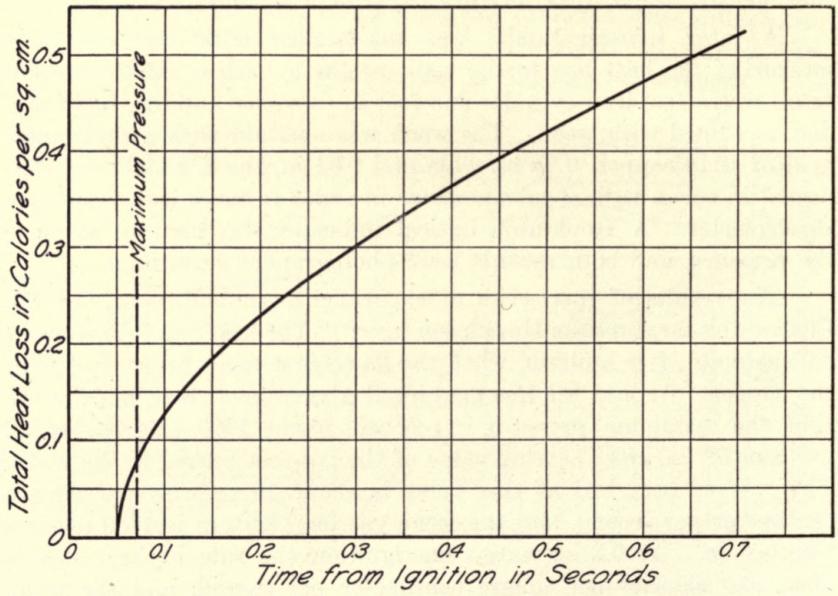


FIG. 35. HEAT LOSS IN EXPLOSIONS OF COAL GAS AND AIR—HOPKINSON

a single high tension spark at the center of the bomb. In all cases the mixture was saturated with water vapor.

Nagel's results contain no record of maximum pressures, since he was interested in the velocity of inflammation alone. For hydrogen and air mixtures he found that this velocity increased directly as the hydrogen content. With a constant mixture the velocity increased with the initial pressure, the increase being greater as the mixture became richer. For illuminating gas and for producer gas the velocity of inflammation also increased with gas content, but at constant gas content there seemed to be a tendency for the velocity to decrease with an increase in initial pressure. This effect was more marked with weak mixtures than with stronger.

The main interest in Nagel's work lies in an elaborate mathematical analysis of the rate of flame propagation in a spherical vessel. In the light of Hopkinson's work it would seem that some of Nagel's conclusions must be somewhat modified. The latter assumed that the time from the passage of the spark for ignition to the time of the attainment of maximum pressure was the time of inflammation. Hopkinson's results, however, prove that the inflammation might be complete, that is, the flame might fill the entire vessel some time previous to the attainment of maximum pressure. This would materially affect some of Nagel's conclusions relative to the rate of flame propagation.

9. *Researches of Bone.*—In 1915 W. A. Bone[172] and several of his students investigated explosions of various mixtures of hydrocarbons with oxygen and air. Two types of explosion vessels were used. One was a cylindrical vessel one foot in diameter and 8 in. long, and the other a spherical vessel 3 in. in diameter. In all cases a Petavel indicator was used to measure the pressures.

These experiments were conducted primarily to make a study of the chemical transformations involved in the explosion process, but the results were also confirmatory of the work of other experimenters on the effect of initial pressure and richness of gas mixture.

10. *Researches of David.*—Major W. T. David[144] has conducted several series of investigations on the explosions of gaseous mixtures with special reference to the cooling of the gas during explosion and the period subsequent to explosion.

In order to determine the effect of radiation, experiments were made in a cylindrical vessel 30 cm. in diameter and length. A Hopkinson indicator was used to record the explosion pressures. The radiation from the mass of gas was measured by means of a platinum bolometer placed in front of a diathermanous fluorite window located in one end. The inside walls of the vessel were either painted black, in order to absorb practically all of the heat radiated by the burning gas, or were silver plated and polished.

Tests were run in the vessel having the blackened walls, using 9 per cent and 15 per cent mixtures of Cambridge coal gas and air. Similar tests were then run in the vessel with polished walls with mixture of 13 per cent and 15 per cent gas content. From these tests the following conclusions were drawn:

(1) The total amount of heat lost to the walls of the vessel by radiation up to the time of maximum pressure is approximately proportional to the product of the third power of the maximum absolute temperature and the time of explosion.

(2) The total radiant heat lost to the walls during the explosion and the subsequent cooling is about 25 per cent of the heat of combustion of the gas.

(3) The emission of radiation at all times varies with the temperature and with the time from ignition.

(4) In weak mixtures (and probably also in stronger mixtures) the rate at which radiation is emitted is a maximum some time before the attainment of maximum pressure, and probably occurs at the time when the flame fills the vessel.

(5) Weak mixtures emit more radiation in the initial stages of cooling than strong mixtures when they have cooled to the same temperature as the weaker.

(6) Carbon dioxide emits radiation about twice as strongly as an equal volume of water vapor at the same temperature.

(7) The total heat lost by radiation up to the time of maximum pressure decreases as the initial pressure of the mixture is increased.

(8) Denser mixtures radiate heat much more strongly than those of less density, especially at the instant of maximum pressure and in the initial stages of cooling. The emission varies approximately as the square root of the density.

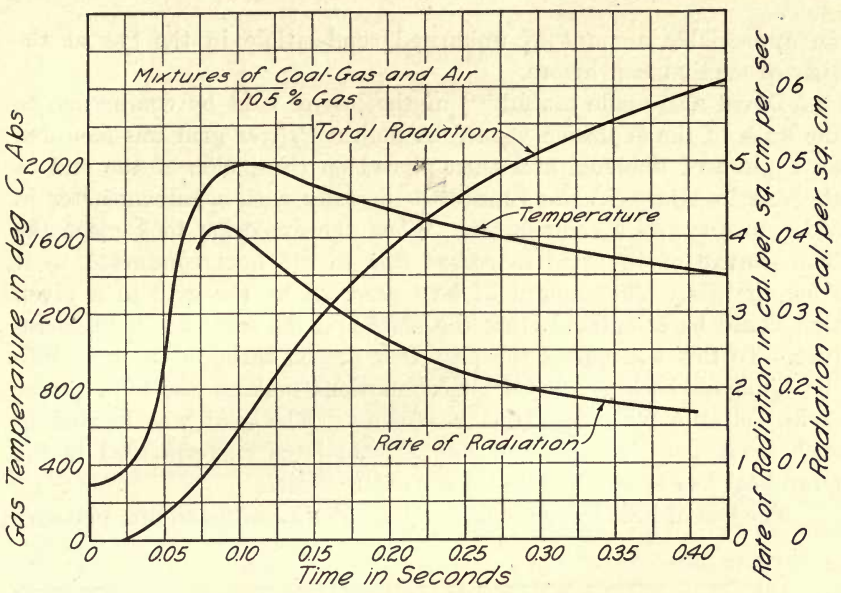


FIG. 36. RADIATION CURVES—DAVID

A set of curves showing the relations between pressure, temperature, total radiation, and radiation per square centimeter of cylinder area is shown in Fig. 36, and others showing the relations between radiation loss in calories per square centimeter per second, size of vessel and initial pressure are shown in Fig. 37. The radiation loss, after correcting for heat absorbed, varies with the temperature very nearly in accordance with Planck's equation for the radiation from a flame of wave length 3.6 μ. At temperatures of 1800 to 2400 deg. C. the radiation varies with the square of the absolute temperature.

In subsequent articles David discusses the radiation from a mass of burning gas from the theoretical standpoint and analyzes his results on a purely mathematical basis.

Tests[196] were made with the same apparatus to determine the effect of diluting the mixture with carbon dioxide instead of the nitrogen in the air. Lower explosion pressures were observed when carbon dioxide was used as a diluent than when nitrogen was used. David attributes this effect to the greater specific heat of carbon dioxide at high temperature and to the fact that dissociation occurs, leaving

an appreciable amount of unburned combustible in the gas at the time of maximum pressure.

David also made a study[215] of the loss of heat by conduction to the walls of the explosion vessel. A polished silver grid was mounted on a piece of linoleum and then placed on the inside of the end of the vessel. The grid was connected in series with a galvanometer in order to serve as a calorimeter. When the explosion took place the temperature of the grid increased due to the heat conducted to it from the gas. The amount of heat received by the grid in a given time could be calculated from the mass and the increase in temperature. To this was added the heat that passed through the grid into the linoleum backing, based on calculations making use of a power series formula with empirical coeffcients. The grid was located in such a manner that the heat loss as calculated corresponded to the mean heat loss by conduction for the entire vessel.

The loss of heat by conduction up to the time of maximum pressure

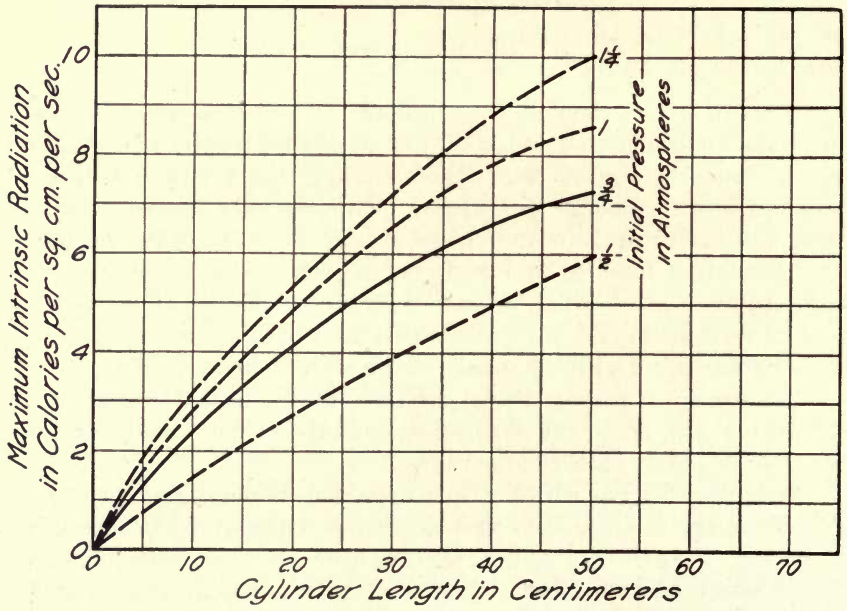


FIG. 37. EFFECT OF INITIAL PRESSURE AND CYLINDER DIMENSIONS ON RADIATION—DAVID

TABLE 20

HEAT LOSS BY CONDUCTION—DAVID

Per Cent Gas in Mixture	Per Cent Heat of Combustion Lost
15.0	5.1
12.4	5.5
9.7	11.0

expressed as a per cent of the heat of combustion of the gas mixtures used is given in Table 20.

The greater time required for the explosion of the weaker mixtures seems to influence the total radiation more than the higher temperatures attained in the case of the stronger, since an increase in heat loss is observed as the mixture becomes leaner.

At 0.5 sec. after ignition the 15 per cent mixture showed a loss by conduction of 38 per cent of its heat of combustion. At the same time the 12.4 per cent mixture had lost about 34 per cent and the 9.7 per cent mixture about 28 per cent of their heats of combustion. Fig. 38 shows the rate of heat loss by conduction during the cooling

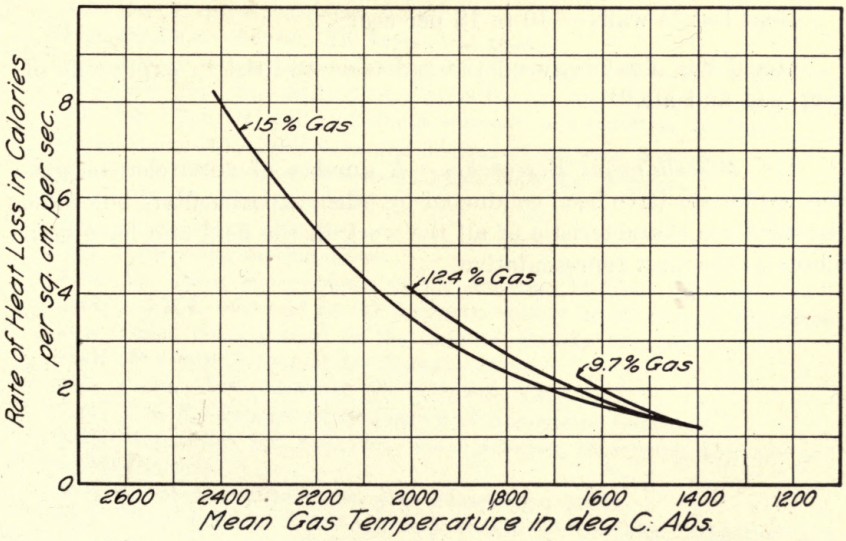


FIG. 38. HEAT LOSS BY CONDUCTION—DAVID

process. In the initial stages of cooling the weaker mixtures seem to lose heat more rapidly than the stronger mixtures when they have cooled to the same temperature. This is probably due to the action of convection currents, which are more effective in the early stages of cooling than in the later.

No mention is made in David's report of any correction having been applied for radiant heat absorbed by the silver grid. Highly polished silver absorbs about 4 per cent of the radiant heat falling upon it,* and it is probable that the grid actually in use absorbed more than 4 per cent due to unavoidable deposits on the surface.

In a later paper David[216] combined the losses due to radiation and conduction, and formed an estimate of the internal energy of the mixture during combustion. The data of this paper indicate that at the moment of maximum pressure about 90 per cent of the heat of combustion of the mixture has been converted into thermal energy, and that after-burning continues for at least 0.025 sec. after maximum pressure is reached. The distribution of energy at the moment of maximum pressure is as follows:

Internal thermal energy — 72 to 80 per cent.
Available chemical energy — 10 per cent.
Heat lost to walls — 10 to 18 per cent.

David has also measured the radiation emitted in explosions of hydrogen and air.[211]

11. *Miscellaneous Researches.*—A number of researches on gaseous explosions have been conducted by other experimenters but those discussed are characteristic of all the work in the field and have been chosen as the most representative.

* Physikalische-Chemische Tabellen, by Landolt and Börnstein, p. 961.

APPENDIX C

Bibliography on Gaseous Explosions

1. *General Statement.*—This bibliography contains references, not only on the subject of the physical phenomena involved in the explosions of gaseous mixtures as considered in this report, but also in regard to the chemical transformations and other allied phenomena. Numerous references of a mathematical nature, particularly in regard to the subject of explosion waves, are also included, as well as some few references describing instruments and apparatus used in investigations of gaseous explosions.

2. *Abbreviations of Titles of Periodicals.*—The titles of various periodicals have been abbreviated when quoted in the Bibliography; therefore the following reference table of abbreviations and full titles is given:

Ann. Chim. et Phys.—Annales de Chimie et Physique.
Ann. des Mines—Annales des Mines.
Ann. der Phys.—Annalen der Physik und Chemie.
Ber. deutsch Chem. Gess.—Berichte der deutschen Chemische Gessellschaft.
Brit. Assn. Adv. Sc.—British Association for the Advancement of Science.
Bul. Soc. l'Ind. Minerale.—Bulletin—Société de l'Industrie Minérale.
Chem. News.—Chemical News and Journal of Physical Science.
Compt. Rend.—Comptes Rendus de l'Académie des Sciences.
Engr.—The Engineer (London).
Eng.—Engineering (London).
Eng. News.—Engineering News.
Jour. Am. Chem. Soc.—Journal of the American Chemical Society.
Jour. A.S.M.E.—Journal of the American Society of Mechanical Engineers.
Jour. Chem. Soc.—Journal of the Chemical Society (London).
Jour. für Gasbel.—Journal für Gasbeleuchtung.
Jour. Prakt. Chem.—Journal für Praktische Chemie.
Jour. S. A. E.—Journal of the Society of Automotive Engineers.
Mem. Manchester Lit. and Phil. Soc.—Memoirs, Manchester Literary and Philosophical Society.
Mitt. ü. Forsch.—Mitteilungen über Forschungsarbeiten.
Phil. Mag.—London, Edinburgh and Dublin Philosophical Magazine and Journal of Science.
Phil. Trans. Roy. Soc.—Philosophical Transactions of the Royal Society.

Phys. Zeit.—Physikalische Zeitschrift.

Proc. Inst. C. E.—Proceedings, Institution of Civil Engineers.

Proc. Inst. M. E.—Proceedings, Institution of Mechanical Engineers.

Proc. London Phys. Soc.—Proceedings of the London Physical Society.

Proc. Roy. Soc.—Proceedings of the Royal Society.

Revue Gen. Elect.—Revue Générale de Électricité.

Sitz. Akad. Wiss. Wein—Sitzungsberichte der Akademie Wissenschaften zu Wein.

Tech. Paper, U. S. Bureau of Mines—Technical Paper, United States Bureau of Mines.

Zeit. Elektro.—Zeitschrift für Elektrochemie.

Zeit. Phys. Chem.—Zeitschrift für Physikalische Chemie.

Zeit. ver. d. Ing.—Zeitschrift des vereines deutscher Ingenieurs.

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The College of Commerce and Business Administration (General Business, Banking, Insurance, Accountancy, Railway Administration, Foreign Commerce; Courses for Commercial Teachers and Commercial and Civic Secretaries)

The College of Engineering (Architecture; Architectural, Ceramic, Civil, Electrical, Mechanical, Mining, Municipal and Sanitary, and Railway Engineering; General Engineering Physics)

The College of Agriculture (Agronomy; Animal Husbandry; Dairy Husbandry; Horticulture and Landscape Gardening; Agricultural Extension; Teachers' Course; Home Economics)

The College of Law (Three-year and four-year curriculums based on two years and one year of college work respectively)

The College of Education (including the Bureau of Educational Research)

The Curriculum in Journalism

The Curriculums in Chemistry and Chemical Engineering

The School of Railway Engineering and Administration

The School of Music (four-year curriculum)

The Library School (two-year curriculum for college graduates)

The College of Medicine (in Chicago)

The College of Dentistry (in Chicago)

The School of Pharmacy (in Chicago); Ph.G. and Ph.C. curriculums

The Summer Session (eight weeks)

Experiment Stations and Scientific Bureaus: U. S. Agricultural Experiment Station; Engineering Experiment Station; State Laboratory of Natural History; State Entomologist's Office; Biological Experiment Station on Illinois River; State Water Survey; State Geological Survey; U. S. Bureau of Mines Experiment Station.

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